Seasonal variation of wave power potential in the coastal areas of India

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Wave-power generation could be a feasible solution to the huge power requirements of a country like India having a long coastline. The present study provides details of wave characteristics and wave power potential during different seasons along the Indian coast using wave observations. Seasonal average of significant wave height (H_s) was computed near the coastal areas of India from the measured data. H_s varied in the range 1.62–1.95 m and 1.38–1.39 m along the west and east coastal areas respectively, during summer monsoon. These high waves generate high wave power (>20 kW/m) along the east and west coastal areas of India. The seasonal average of wave power obtained was high (12–19 kW/m) off the west coast of India, suggesting that the west coastal areas are suitable for power generation during summer monsoon. This study highlights that the average wave power is high (12–19 kW/m) during summer monsoon along the west coast and insignificant (<2 kW/m) during non-monsoon. Thus the present study suggests employing a to hybrid arrangement of power generation using solar and ocean wave energies to solve the problem of energy deficit near the coastal areas of India.

Keywords: Coastal areas, power generation, significant wave height, summer monsoon, wave power potential.

A global increase in population, economic expansion and transportation has led to an increase in energy consumption in the last 50 years. Researchers have explored renewable resources to meet the energy demands[1]. As conventional energy resources deplete gradually, the main attention has shifted to renewable energy sources[2]. Among the various renewable sources, the most easily available is wave energy from the oceans. Available wave power from the ocean was ~32,000 TWh/year (refs 1, 3), in the year 2015, whereas global electricity production was ~23,950 TWh (refs 1, 4). There is a huge demand for electricity, especially in developing countries. India receives a good amount of sunshine throughout the year. However, during the monsoon months i.e. from June to September, the west coast of India receives heavy rainfall and the sky is mostly covered with clouds. Solar irradiation decreases drastically during these months, but wave energy increases substantially due to a rise in significant wave height and wave period[5]. This wave energy can be harnessed using oscillating water columns for the generation of electricity. A hybrid arrangement for the generation of wave energy and solar energy can solve the problem of energy deficit near the remote coastal areas of India[5].

A seasonally reversing monsoon winds play a crucial role in affecting wave characteristics during pre-monsoon (PM), summer monsoon (SM) and northeast monsoon (NM) in the north Indian Ocean and coastal areas of India[6,7]. Understanding the seasonal variation of wave characteristics is essential for adequate design and construction of coastal structures and wave energy converters which are useful for power generation. Previous studies on wave power generation shows that high wave power potential is observed along the Indian coast during SM[1,8,9]. It has also been reported that about 55–65% of annual total wave power is contributed by the coastal areas of India during SM[10]. Wave power was the lowest ~(2.6 kW/m) during NM and highest ~(25.9 kW/m) during SM along the west coast of India[11]. High wave power observed during SM along the Indian coast is due to an increase in wave energy near the coastal areas. The consistency of wave power availability at a location is an important input parameter for the effective harnessing of power from that location. Wave power is not continuously high throughout the year, seasonal variations are observed near the coastal areas of India. The bulk wave parameters (significant wave height H_s, peak wave period T_p and peak wave direction P_{dir}) provide a good account of the wave characteristics which are essentially required for the construction of any coastal structure[12,13].

Keeping these points in view, the present study provides the seasonal variations of wave parameters and wave power near the shallow-water locations along the Indian coast. The observed wave data collected from the data well Waverider buoy (DWRB) at eight different locations along the Indian coast have been used in the study. In the Indian scenario, few studies are available for wave power estimations near shallow-water locations based on the measured and modelled data[1,9,11,14]. The present study is one among them, as it mainly discusses seasonal variations of wave parameters and wave power near the coastal areas of the country.

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Materials and methods

The present study utilizes measured data from DWRB at eight coastal stations maintained by Earth System Science Organization – Indian National Centre for Ocean Information Services (ESSO-INCOIS) (Figure 1). Buoy data were available at four coastal stations (Tuticorin, Puducherry, Gopalpur and Digha) along the east coast and four coastal stations (Karwar, Ratnagiri, Versova and Okha) along the west coast for 2016 (Figure 1). DWRB measures horizontal (roll and pitch) and vertical (heave) accelerations using two accelerometers and an on-board compass which gives directional displacements in two horizontal axes[9]. The displacements are converted to wave parameters using in-built software in the buoy. DWRB measures waves with periods in the range 1.6–30 sec, and heave motion in the range –20 to +20 m with a resolution of 1 cm. Wave-direction measurement was obtained in the range 0°–360° with a directional resolution of 1.5° and accuracy of 0.5° with reference to the magnetic north. The buoy data records were taken at a frequency of 1.28 Hz for 17 min every half an hour. Quality check of the measured time series data was done for standard errors such as spikes, steepness and constant signals[15,16]. The buoy wave spectra were obtained using fast Fourier transform. Different wave parameters like H_s, T_p and P_{dir} were derived from the wave spectrum using the following equations.

$$H_s = 4\sqrt{m_0}, \tag{1}$$

$$T_e = \frac{m_{-1}}{m_0}, \tag{2}$$

$$T_p = \frac{1}{f_p}, \tag{3}$$

$$P = \rho g \int_0^{2\Pi} \int_0^{\infty} C_g(f, d) S(f, \theta)\, df\, d\theta, \tag{4}$$

Here m_0 is the zeroth moment and m_{-1} is the reciprocal of the first spectral moment. H_s is derived from the spectrum using eq. (1). T_p (sec) is defined as the wave period associated with the most energetic waves in the total wave spectrum at a specific frequency. P_{dir} is the direction associated with the highest energetic wave in the total wave spectrum. The wave period parameter used in the wave power analysis is called the energy period (T_e). Wave parameters were converted to wave power (P) using eq. (4), where ρ is the density of water, g is the acceleration due to gravity, C_g is the group velocity, $S(f, \theta)$ is the directional wave spectrum, f is the frequency, d is the water depth and θ is the wave direction[9]. The real-time data were received from INCOIS through the Indian National Satellite System (INSAT)/Global System for Mobile Communication (GSM) modes. The present study discusses the wave characteristics during different seasons; January–April as PM, May–September as SM and October–December as NM.

Results and discussion

In this section we discuss seasonal variations of wave characteristics and wave power near the coastal areas of India by analysing observation data. A description of general wave characteristics along the Indian coastal areas is given first to provide support for the wave power potential description at different coastal locations.

Seasonal variations of wave characteristics near the coastal areas of India

Figure 2 *a* and *b* shows time-series plots of H_s near the east coast (Tuticorin, Puducherry, Gopalpur and Digha) and west coast (Karwar, Ratnagiri, Versova and Okha) during 2016. $H_s \sim$ (1 m) was observed most of the time near the east coast of India during PM, indicating calm wave conditions during this season (Figure 2 *a*). As SM begins, H_s variations are in the range 1–2 m at Tuticorin and Puducherry 1–3.6 m near Gopalpur and Digha. The impact of SM is high at Gopalpur and Digha compared to Tuticorin and Puducherry. Except for extreme conditions, H_s was observed to be relatively low (0.5–1.5 m) during the October to December NM season. Maximum H_s of 3.55 m was recorded at Gopalpur during SM and minimum of 0.21 m at Tuticorin during NM. Greater wave heights (2–3 m) were observed off Gopalpur, Digha and Puducherry during May, November and December due to extreme events formed in the Bay of Bengal (BoB). Mean H_s was observed to be high (0.96–1.39 m) (Table 1) during SM, 0.72 m at all east coastal locations except Puducherry,

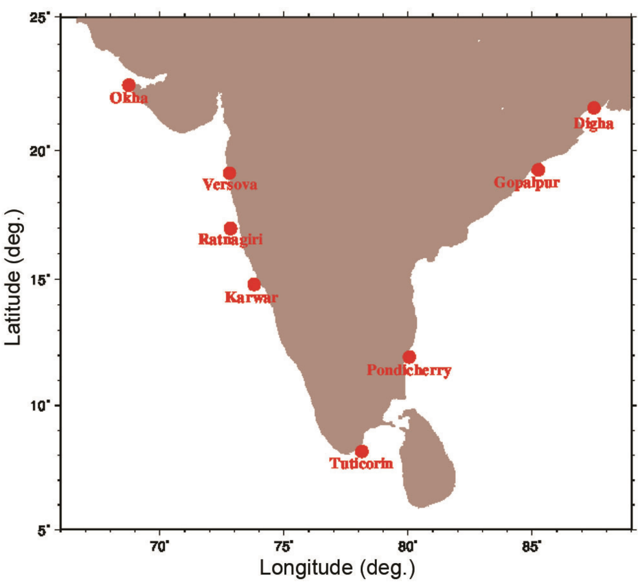

Figure 1. Data well wave rider buoy locations along the east and west coasts of India.

Table 1. Statistics of (significant wave height (H_s) and peak-wave period (T_p)) computed from the DWRB data along the east coastal area of India

Control area	H_s (m) Pre-monsoon (PM)	H_s (m) Summer monsoon (SM)	H_s (m) Northeast monsoon (NM)	T_p (s) PM	T_p (s) SM	T_p (s) NM
Tuticorin	0.76	0.96	0.77	11	13	11
Puducherry	0.69	0.72	0.82	6	9	8
Gopalpur	0.85	1.38	–	11	13	–
Digha	0.91	1.39	0.74	11	12	13
Karwar	0.73	1.92	0.64	11	11	13
Ratnagiri	0.74	1.95	0.49	10	11	13
Versova	–	1.62	0.50	–	11	11
Okha	0.33	1.81	–	9	10	–

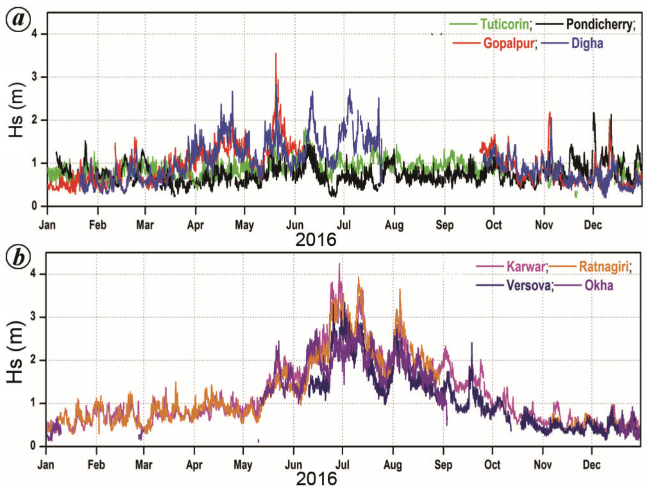

Figure 2. Time series plots of significant wave height in the (***a***) east and (***b***) west coasts of India.

whereas low values in the range 0.69–0.91 m were observed during PM and NM. The highest mean values of H_s were varied in the range 1.38–1.39 m off Gopalpur and Digha during SM and low values were observed off Puducherry (0.69 m) during PM. It is interesting to note that mean H_s increased from Tuticorin to Digha during PM and SM, and was almost constant during NM, suggesting the prevalence of greater wave heights near the high latitudes off the eastern coastal areas of India. Wave heights near Karwar and Ratnagiri were predominantly low (<1 m; Figure 2 *b*) during PM and continuously high (H_s > 1.5 m) throughout SM. The observed H_s was maximum off Karwar and Ratnagiri (2–4 m) and off Versova and Okha (2–3 m). The strong SM winds generate high waves near the west coastal areas of India with mean values of 1.62–1.95 m. Mean values of H_s varied in the range 0.33–0.73 m (Table 1) indicating calm waves prevailing near the west coastal areas during PM and NM. It is interesting to note that mean H_s decreased from Karwar to Okha irrespective of the season, suggesting the prevalence of high waves at low latitudes off the western coastal areas.

Figure 3 *a–c* shows scatter plots of T_p and P_{dir} near the east coastal areas of India. T_p varied from 4 to 25 sec at all the east coastal locations, except Puducherry, confirming a mixed state of wind sea and swell during PM and NM. T_p < 8 sec observed most of the time at Puducherry suggests the predomination of wind waves at this coast during PM (Figure 3 *a*). Long-period swells from the southern Indian Ocean (SIO) were not seen at Puducherry due to the shielding effect of Sri Lanka Island[17]. P_{dir} varied from 90° to 150° off Tuticorin and Puducherry, and from 135° to 210° off Gopalpur and Digha, suggesting the predominance of E–SE–S waves near the eastern coastal areas of India during PM and NM (Figure 3 *a*). T_p varied in the range 5–16 sec during SM at all east coastal areas (Figure 3 *b*). Further P_{dir} showed waves from 110° to 180° near Puducherry and 150° to 180° in rest of the locations (Figure 3 *b*). The combination of T_p with P_{dir} suggests the dominant swell propagation from SIO in the eastern coastal areas during SM. It is interesting to note that the propagation of waves from N–NE was also observed at Digha during all seasons. Figure 3 *d* and *f* shows the propagation of long-period swells (10–20 sec), wind seas (3–7 sec) and shamal swells (5–10 sec) along with the directions S–SW–W, W–NW and NW respectively, off the west coast of India during PM and NM, revealing the complex sea state near the west coastal areas. The shamal swells originate from the NW Arabian Sea and reach the west coast of India during PM and NM seasons[18]. Propagation of swells (10–15 sec) and wind seas (3–5 sec) was observed along SW–W and NW–N respectively, during SM off the west coastal areas (Figure 3 *e*). Table 1 shows the mean values of T_p near the coastal areas during different seasons. The mean value of T_p at Puducherry is different from other coastal locations. The mean value of T_p (6 sec) at Puducherry shows dominant wind waves during PM[6]. Along with the west coastal areas of India, mean values of T_p were observed to be slightly high during NM (11–13 sec) compared to PM (9–11 sec) and SM (10–11 sec).

Seasonal variation of wave power potential near the coastal areas of India

Seasonal variability of wave power (WP) is an important factor in the selection of the location for a wave power

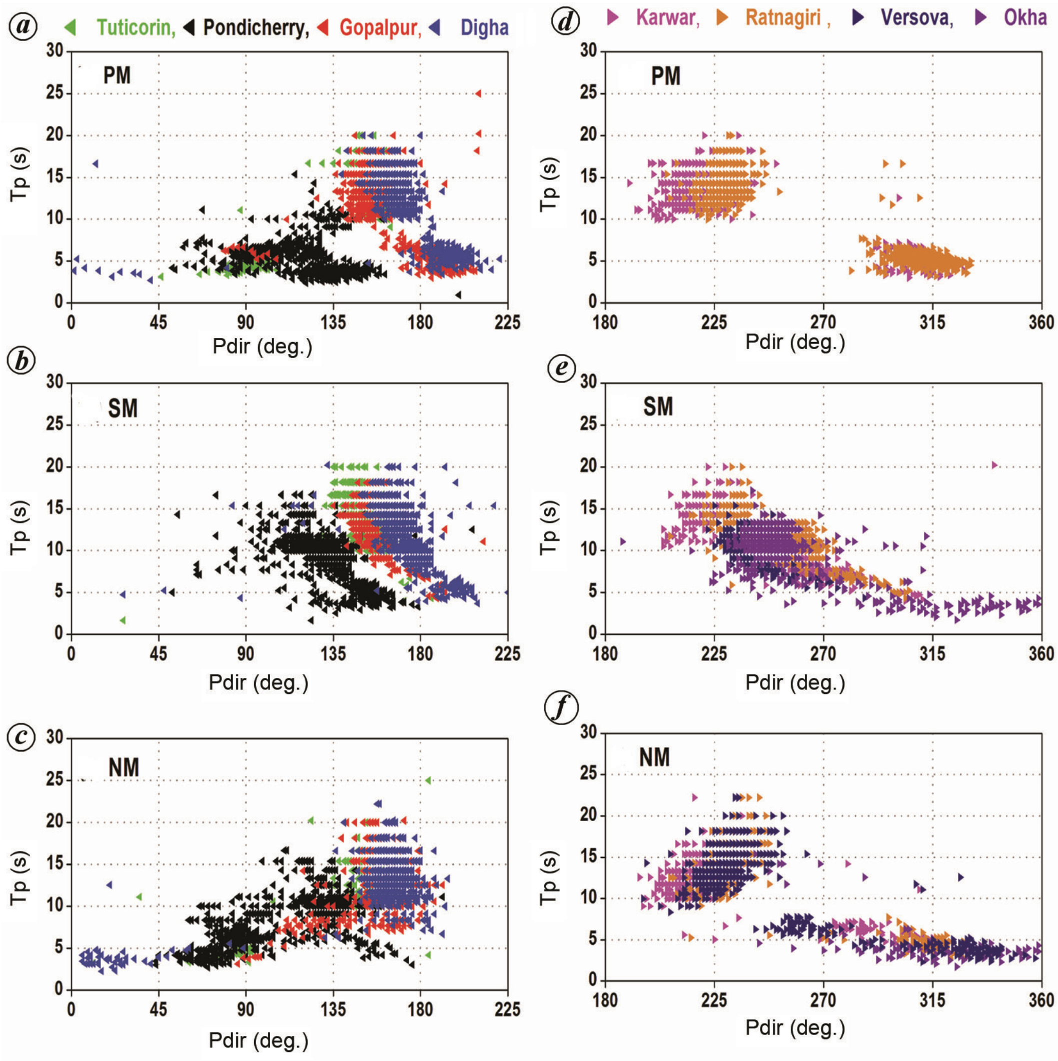

Figure 3. Scatter plots of peak wave period and peak wave direction during pre-monsoon (PM), summer monsoon (SM) and northeast monsoon (NM) seasons in the (***a–c***) east and (***d–f***) west coasts of India.

plant. Equation (4) is used for the computation of wave power potentials (WPP) near the coastal areas of India. Figure 4 displays the time-series plots of WPP off the coastal areas. High WP > 20 kW/m was observed off the east coastal areas (Gopalpur and Digha) during SM with highest powers of 98 and 52 kW/m respectively (Figure 4 *a*). Highest WP obtained during May near these coastal areas was due to the presence of high waves generated from cyclone Roanu. WP was slightly higher at Gopalpur and Digha compared to Tuticorin and Puducherry (Figure 4 *a*). Maximum WP (10–18 kW/m) was observed near Tuticorin and Puducherry under normal conditions and it was 20–30 kW/m under extreme conditions. WP was comparatively high at Gopalpur compared to the other east coastal locations. Gopalpur coast is inclined slightly higher 45° to the east from the true north, which causes refraction of the waves approaching the shore. Also, the coast experience high energetic swells from SIO, strong wind waves during SM and the dominant effect of extreme events which together contribute to its increasing WP. Seasonal average wave power (AWP) calculated along the coastal areas showed high values (10–15 kW/m) off Gopalpur and Digha during SM and low values (<5 kW/m) during PM and NM (Figure 4 *c*).

Along the west coast, high values of WP (>20 kW/m) were observed during SM and low values (~10 kW/m) during rest of the seasons (Figure 4 *b*). WP was continuously high throughout SM and maximum values were observed off Karwar (96 kW/m), Ratnagiri (82 kW/m), Versova (55 kW/m) and Okha (47 kW/m). AWP varied in the range 12–19 kW/m off the west coast, with the highest off Karwar and Ratnagiri (18–19 kW/m), and off Versova and Okha (12–14 kW/m) during this season (Figure 4 *c*). It is interesting to note that the values of WP and AWP found were high at Karwar and Ratnagiri than Versova and Okha. From eq. (4), it is clear that WP is dependent on wave energy, which is linearly related to H_s. From Figure 2 *a* it can be seen that H_s is high near Karwar and

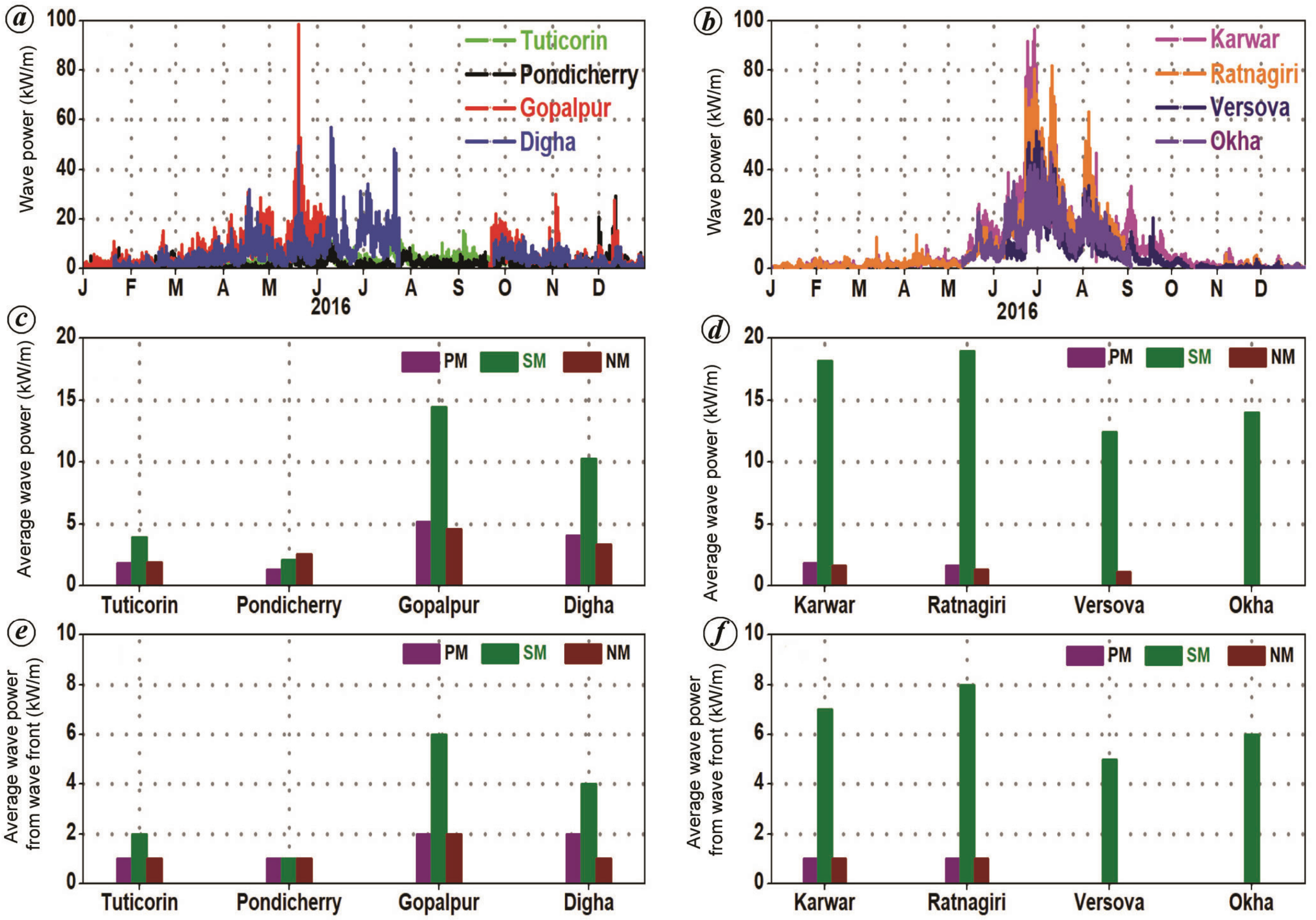

Figure 4. Annual time series of wave power along the (***a***) east and (***b***) west coastal areas of India. ***c***, ***d***, Average wave power off the (***c***) east and (***d***) west coastal areas. Average wave power from wavefront off the (***e***) east and (***f***) west coastal areas.

Ratnagiri (2–4 m) than Versova and Okha (2–3 m). These high waves generated high WPs near Karwar and Ratnagiri. Along the west coast, AWP values were observed to be low (<2 kW/m) during PM and NM and increased during SM (12–19 kW/m). High AWP makes the west coastal areas suitable for power generation during SM. It is important to note that high values of AWP were observed only during SM and were insignificant (<2 kW/m) during PM and NM. Hence ocean wave energy is not sufficient to generate power near coastal areas.

It is a known fact that India has a tremendous amount of solar energy for power generation. However, during SM, the west coast of India experiences heavy rainfall leading to insufficient solar power generation[5]. However, WP increases during SM (Figure 4 *b*). A hybrid arrangement of power generation using solar energy and wave energy with stand-alone micro grids can solve the problem of energy deficit near the coastal areas of the country[5]. Overall monsoon waves in the range 2–4 m generated high WP near the west coastal areas of India. It is important to understand how much WP could be derived from each wavefront before the installation of wave energy converters (WECs). In the present study, the estimated power generation from each wavefront was computed using the below equation[19].

Estimated power generation from each wave front

= WP * 0.40.

Figure 4 *e* and *f* shows AWP from each wavefront during different seasons. It is clear from a figure that the west coastal areas of India have higher prospects of trapping wave energy (5–8 kW/m) than the east coast (<6 kW/m). Further, it is noticed that WP is significant during SM; hence we have studied variations of WP with wave parameters (P_{dir}, T_{p}, H_{s}) during this season (Figure 5). The scatter plot shows high WP (>20 kW/m) observed along the directions SE–S and SW–W off east and west coasts respectively (Figure 5). The linear dependency of WP versus H_{s} is consistent than WP versus T_{p} in all coastal areas of India.

Conclusion

The present study discusses seasonal variation of wave characteristics and wave power near the coastal areas of

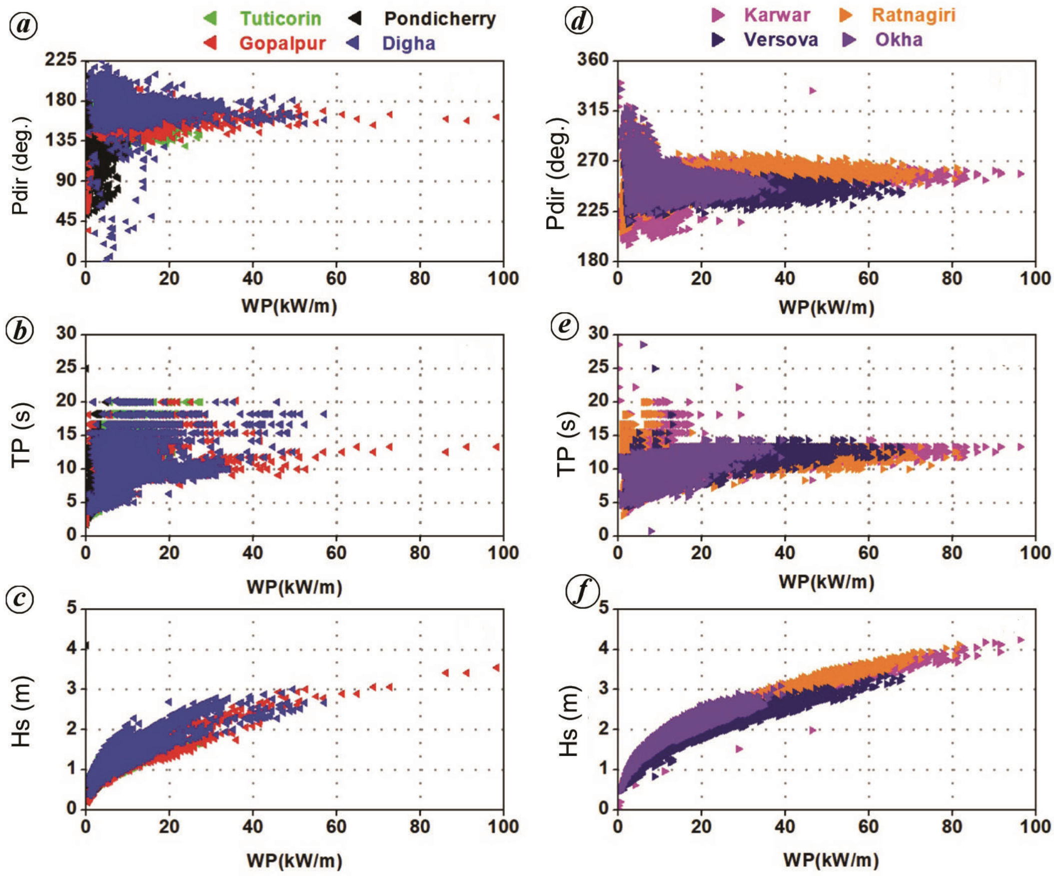

Figure 5. Scatter plots of wave parameters (P_{dir}, T_p, H_s) with wave power (WP) off the (***a–c***) east coastal and (***d–f***) west coastal areas of India during SM.

India during PM, SM and NM. The study utilizes observation data collected from eight stations (Tuticorin, Puducherry, Gopalpur, Digha, Karwar, Ratnagiri, Versova and Okha) of the DWRB network in the Indian coastal waters. The wave characteristics show H_s < 2 m during PM and NM indicating presence of calm wave climate near the coastal areas of India. During SM, mean values of H_s were found to be high, i.e. 0.96–1.39 m and 1.62–1.95 m off the east and west coasts of India respectively, suggesting the prevalence of high waves near the coastal areas. Extreme conditions also cause greater wave heights near the eastern coastal areas of India. Mean values of T_p at Puducherry show dominant wind sea during PM and coexistence of wind sea and swell near coastal waters of India during NM. WP variations were found to be significant only during SM along the coastal areas of India. During SM, high WP (>20 kW/m) was not seen in the southeast coastal areas (Tuticorin and Puducherry) due to the shielding effect of Sri Lanka. Due to strong monsoon waves and orientation of the coastline, high WP was observed near the northeast coastal areas (Gopalpur and Digha) with a seasonal average of 10–15 kW/m. Also, high WPs were observed along the east coast during extreme conditions. Along the west coast, the highest WP was observed near Karwar (96 kW/m) and Ratnagiri (83 kW/m) with a seasonal average of 18–19 kW/m during SM. The seasonal average of WP along the west coast was found to be high (12–19 kW/m), suggesting that these areas are suitable for power generation. High WP was observed along SE–S and SW–S directions off the east and west coastal areas respectively, during SM. The WP values were found to be insignificant during NM. Hence this study suggests that a hybrid arrangement of power generation using wave energy and solar energy can solve the problem of energy deficit in the remote coastal areas of India.

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