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# Wave energy resource assessment for the Indian shelf seas

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A B S T R A C T

As a renewable energy, the assessment of wave power potential around a country is crucial. Knowledge of the temporal and spatial variations of wave energy is required for locating a wave power plant. This study investigates the variations in wave power at 19 locations covering the Indian shelf seas using the ERA-Interim dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim data is compared with the measured wave parameters in the Arabian Sea and the Bay of Bengal. Along the western shelf seas of India, the seasonal oscillations lead to variation of the wave power from the lowest seasonal mean value (2.6 kW/m) in the post-monsoon period (October–January) to the highest value (25.9 kW/m) in the south-west monsoon (June–September) period. Significant (10–20%) inter-annual variations are detected at few locations. The mean annual wave power along the eastern Indian shelf seas (2.6–9.9 kW/m) is lower than the mean annual wave power along the western part (7.9–11.3 kW/m). The total annual mean wave power available along the western shelf seas of India is around 19.5 GW. Along the eastern shelf seas, it is around 8.7 GW. In the Indian Shelf seas, the annual mean wave power is highest (11.3 kW/m) at the southern location (location 11), and the seasonal variation in wave power is also less. Hence, location 11 is a better location for a wave power plant in the Indian shelf seas.



## 1. Introduction

Amongst renewable energy sources, ocean waves contain the highest energy density and have the potential to become a commercially viable energy source [1]. Progress from full-scale testing to the commercialisation of wave energy projects has been relatively slow. This slowness has been partly due to the financial risks associated with uncertainty in quantifying the wave energy resource over a variety of timescales [2]. Based on the analysis of wave data collected from buoys, satellites, numerical wave hindcasts, or a combination of these sources, wave energy resource assessments have been made for the Black Sea [3], the Baltic Sea [4], the Hawaiian Islands [5], the North Sea [2] and the Persian Gulf [6]. In addition, wave energy resource assessments have been made for the seas around Australia [7], Canada [8], California [9], Canary Islands [10], China [11], Europe [2,12], Iran [13], Ireland [14], Malaysia [15], Portugal [16,17], Taiwan [18], the United Kingdom [2,19] and the United States [20,21]. Wave energy resource assessment is also carried out globally [22,23].

India has a long coastline of 5423 km along the mainland and receives around 5.7 million waves per year [24,25]. Hence, the country has large wave energy resources. Along the Indian coast, the Indian Institute of Technology Madras in Chennai has conducted studies on wave energy resources and wave energy conversion devices [26]. In addition, a wave energy plant is located at Vizhinjam based on the near-shore oscillating water column [27].

Kumar et al. [28] examined variations in near-shore wave power at four shallow water locations along the east and west coasts of India. Their findings were based on the measured wave data covering a one-year period. However, since the spatial and temporal variation in wave energy covering the entire Indian shelf seas is not known, the purpose of this research is to assess the wave energy resources in the Indian shelf seas. Nineteen deep water locations (11 locations in the western Indian shelf seas and 8 locations in the eastern Indian shelf seas) are selected for the study (Fig. 1). Information on the monthly and annual variability of the wave power is required when selecting a wave power plant location. Hence, the variations in wave power over a 34-year period at the 19 deep water locations are also studied.

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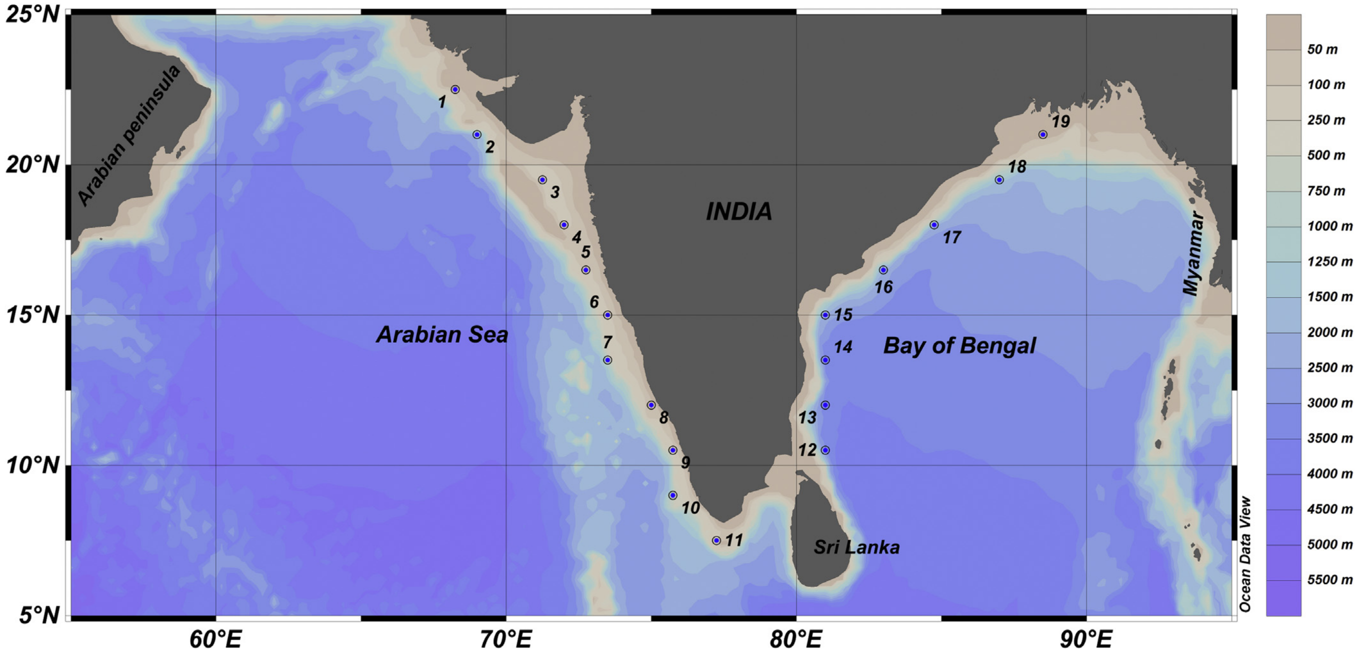


**Fig. 1.** Map showing the locations considered in the study.

## 2. Materials and methods

### 2.1. Data

The ERA-Interim (ERA-I) global atmospheric re-analysis dataset, the most recent reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), is used in the study [29]. An updated atmospheric model (the Integrated Forecast System Cycle 31r2) is used in the data analysis, which includes increased pressure levels and additional cloud parameters that maximize improved model physics [30]. The incorporated wave model is based on the WAM (global ocean WAve prediction Model) approach [31]. Significant wave height ($H_s$) and wave period ($T_e$) data with a grid resolution of 0.75° × 0.75° are extracted for the period January 1, 1979 to December 31, 2012 at 6-h intervals for the selected locations.

Although the ERA-I datasets are validated with measured buoy data for different regions [32], the ERA-I $H_s$ and $T_e$ data are compared with the measured buoy data at two locations in the Arabian Sea (AS) and at one location in the Bay of Bengal (BoB) before estimating wave power in the Indian shelf seas. The location of the buoys and the details of the data collected are presented in Table 1. Using the heave data recorded by the buoy, the wave spectrum is obtained via Fast Fourier Transform (FFT). The $H_s$ and the energy wave period ($T_e$) are obtained from the spectral moments as shown in Equations (1) and (2).

$$\text{Significant wave height } (H_s) = 4\sqrt{m_0} \tag{1}$$

$$\text{Energy period}(T_e) = \frac{m_{-1}}{m_0} \tag{2}$$

where $m_n$ is the nth order spectral moment and given by $m_n = \int_0^\infty f^n S(f)\mathrm{d}f$, $n = 0$ and $-1$, and $S(f)$ is the spectral energy density at frequency $f$.

### 2.2. Comparison of ERA-I data with buoy-measured data

Comparisons of the $H_s$ from the ERA-I and the buoy-measured data show good agreement (Fig. 2). The quantitative assessment is done based on the error indices (bias, correlation coefficient and root mean square error). The correlation coefficient ($r$) value for the $H_s$ is 0.96 with a bias value of 0.17 m. For the shallow water location in the AS, the maximum $H_s$ value is the same (4.4 m) for buoy-measured and ERA-I data. In contrast, in deep water, the ERA-I data underestimate the $H_s$ for values more than 3.5 m in the AS and for values more than 2.5 m in the BoB (Fig. 2). For example, the average value of the buoy-measured $H_s$ at 2 locations in the AS is 2.1 and 2.5 m, while the average value of the $H_s$ from the ERA-I data for the same period is 1.9 and 2.6 m. In addition, the average value of buoy-measured $H_s$ in the BoB is 1.5 m, whereas the $H_s$ determined by ERA-I is 1.4 m. The difference between the mean value of the

**Table 1**
Details of buoy data used for comparison with ERA-Interim data.

| Buoy location | ERA-Interim data | Period | Instrument used for wave measurement | Data recording | Details of data analysis |
|---|---|---|---|---|---|
| 16.953° N, 71.047° E (Arabian Sea: location 1) | 17.25° N, 71.25° E | May–December 2005 | Seatex buoy (Oceanor, Norway) | 17-min duration at 2-Hz interval | National Data Buoy Programme [33] |
| 13.978° N, 83.260° E (Bay of Bengal) | 14.25° N, 83.25° E | July 2004–May 2005 | | | |
| 20.740° N, 70.658° E (Arabian Sea: location 2) | 20.50° N, 70.50° E | June–August 2009 | Directional waverider buoy (Datawell, Netherlands) | 30-min duration at 1.28-Hz interval | Kumar et al. [34] |

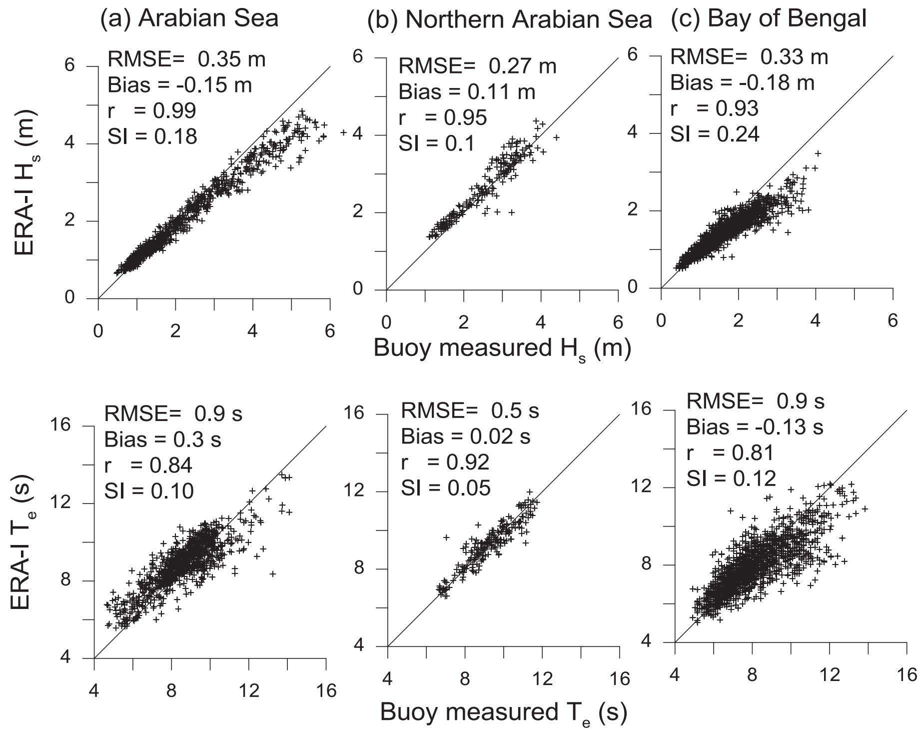


**Fig. 2.** Scatter plot of buoy measured $H_s$ with ERA-I $H_s$ (top panel) and buoy measured $T_e$ with ERA-I $T_e$ (bottom panel) for 3 locations.

buoy-measured $H_s$ and the ERA-I $H_s$ is low (<0.2 m in the AS and the BoB), whereas the difference between the maximum $H_s$ value is high (~1.5 m in the AS and 0.6 m in the BoB).

The comparisons of ERA-I wave period data with the buoy-measured $T_e$ show that the scatter is less with a good correlation coefficient (0.8–0.9) and bias values less than 0.3 s (Fig. 2). The difference in the average $T_e$ between the measured and the ERA-I data is negligible (<0.3 s) and the difference in the maximum value of $T_e$ is less than 1.6 s. The study shows that ERA-I $H_s$ and $T_e$ data can be used with confidence for studying the wave power potential in the AS and the BoB.

In some of the earlier studies since energy period ($T_e$), values were not available. The same was estimated from the known peak wave period ($T_p$) using the expression $T_e = 0.9 \times T_p$ [6,12]. The comparison of $T_p$ with $T_e$ based on the measured data shows larger scatter for values of $T_p$ more than 12 s (Fig. 3). The study shows that, for locations like the AS and the BoB where long period swells ($T_p > 12$ s) are present, estimating wave power using $0.9 \times T_p$ as the energy period will lead to overestimation of $T_e$ for values more than 10 s and underestimation of $T_e$ for values less than 10 s. Kumar et al. [28] also found that the expression $T_e = 0.9 \times T_p$ is not valid at four shallow water locations around India when $T_p$ is more than 8 s.

### 2.3. Wave power estimation

Wave energy flux (i.e., wave power transmitted per unit width) for deep water locations is estimated using the expression:

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \quad (3)$$

where $P$ is the wave power per unit of crest length (kW/m), $\rho$ is the density of seawater (kg/m$^3$), g is the gravitational acceleration (m/s$^2$), $H_s$ is the significant wave height ($m$) and $T_e$ is the energy period(s).

## 3. Results and discussion

### 3.1. Distribution of annual mean wave power in the Arabian Sea and the Bay of Bengal

The spatial distribution of the annual mean wave power in the AS and the BoB is presented in Fig. 4. The annual mean wave power is the highest (15–20 kW/m) in the southern BoB. The annual mean wave power is relatively high (~12 kW/m) in the central AS and off the southern tip of India. The wave power off the southeast coast of India is the lowest (<5 kW/m) due to the presence of Sri Lanka. The variability of the wave power in monthly, seasonal and annual scales needs to be known before selecting a location for a wave power plant since locations with steady wave power are more attractive than locations with large seasonal and annual variations. Hence, this study examines monthly, seasonal and annual wave power variations at 19 locations covering the western and eastern shelf seas of India. The results are presented in the next sections.

### 3.2. Monthly variations in wave power

The monthly mean wave power variation at 19 locations in the Indian shelf seas is presented in Fig. 5. At all locations in the AS, the monthly mean wave power is highest during the month of July followed by the month of June. The standard deviation of monthly variation is the highest (~2 kW/m) at Locations 4–7, indicating larger variability at these locations compared to other locations. The highest monthly mean wave power occurs at Location 2 (39.3 kW/m in July) followed by Location 4 (38 kW/m). The global study by Arinaga and Cheung [23] reported a monthly median wave power of 72 kW/m in the Arabian Sea in July. The mean wave power during June–August is more than 20 kW/m at Locations 8–11 and more than 25 kW/m at Locations 1–7 (Fig. 5). At all locations in the western BoB, the monthly mean wave power is highest during June followed by July (Fig. 5). The monthly mean

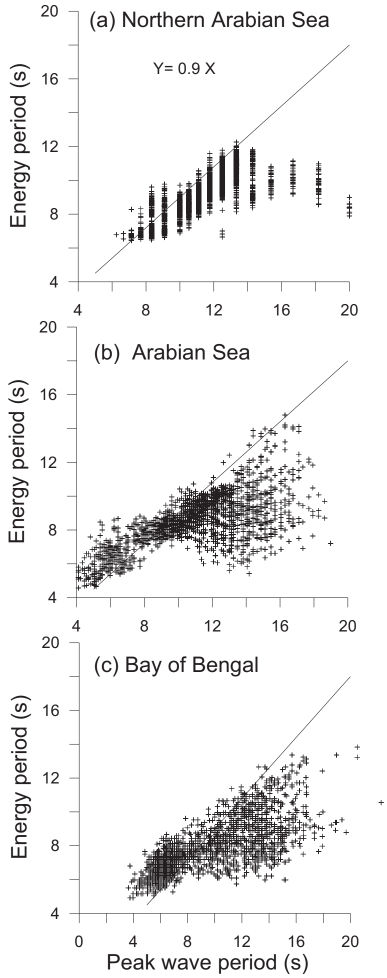


**Fig. 3.** Scatter plot of the peak wave period and energy period based on measured data.

wave power in June varied from 3.7 kW/m (Location 12) to 18.8 kW/m (Location 18).

The monthly maximum wave power is highest during June at all locations in the AS except at Locations 10 and 11. At these locations, the monthly maximum wave power occurs during July (Fig. 6). Compared to other months, the spatial variation in the mean wave power during June is high (52 kW/m at Location 11–210 kW/m at Location 5). Locations 5 and 6 have the highest monthly maximum

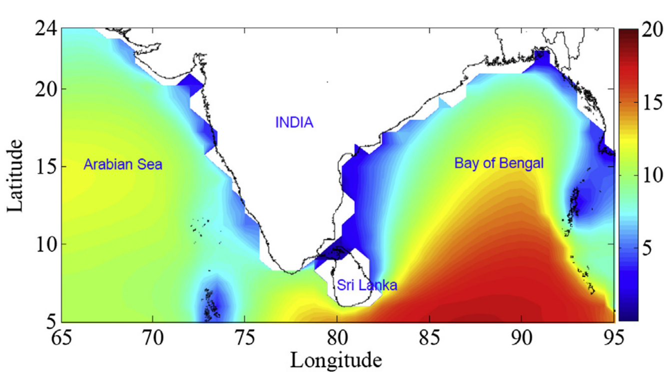


**Fig. 4.** Distribution of annual mean wave power in Arabian Sea and Bay of Bengal. The unit of wave power is kW/m.

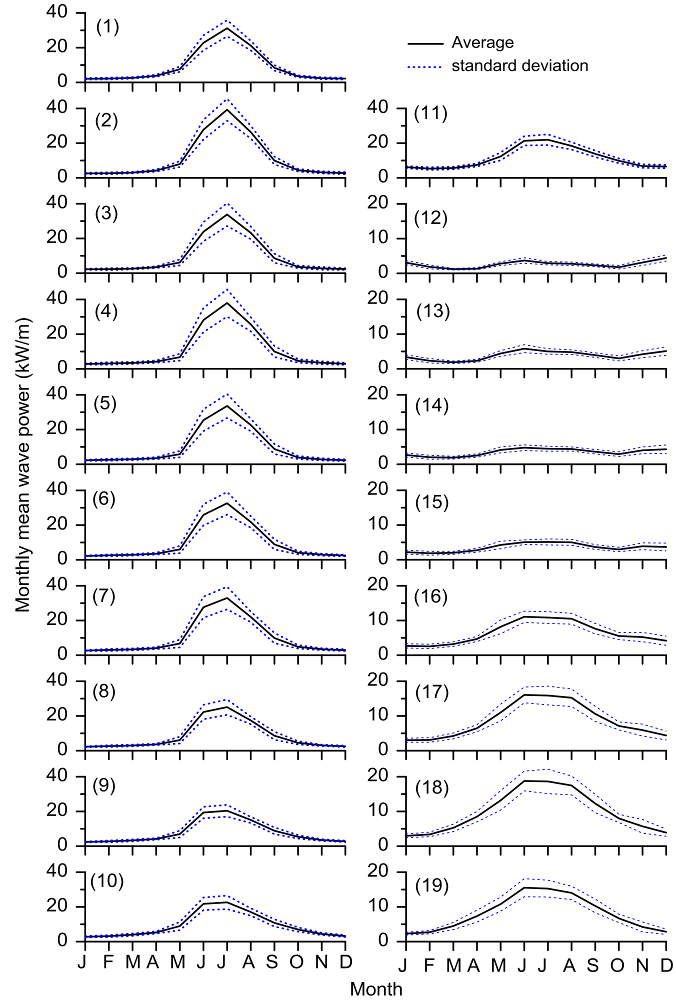


**Fig. 5.** Annual cycle of monthly mean wave power along the eastern Arabian Sea (1–11) and western Bay of Bengal (12–19).

wave power (203–210 kW/m). From December to April, the mean monthly maximum wave power is less than 20 kW/m at all locations in the AS.

In the BoB, the monthly maximum wave power is highest during July at northerly locations (15–19) and is during December at southerly locations (12–14) (Fig. 6). Locations 17 and 18 have the highest monthly maximum wave power (130 kW/m) in the BoB (recorded in July).

A monthly variability index (MVI) is used to determine the monthly variability in wave power [35]. The MVI is estimated as the ratio of the difference between the maximum and minimum monthly mean wave power and the annual mean wave power. Small values of MVI indicate less variability in wave power. The results of this study indicate that the wave power variability is more at Locations 1–7 with MVI values more than 3 and that it is less (~1.5) at Locations 11–17 (Fig. 7a).

### 3.3. Seasonal variations in wave power

The waves in the Indian shelf seas show seasonal variations [24,25] with high waves (>1.5 m) during the SW monsoon period (June–September). October–January is the post-monsoon period while February–May is the pre-monsoon period. Hence, the seasonal variations in wave power are studied. The findings show that the highest seasonal mean wave power occurs during the SW

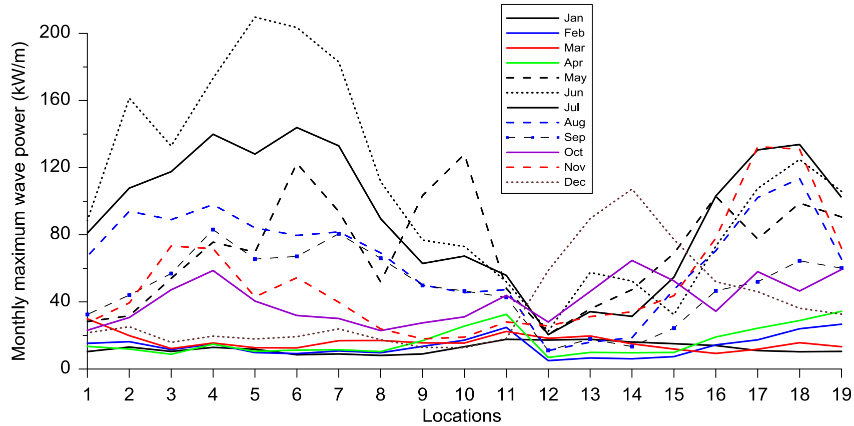


**Fig. 6.** Monthly maximum wave power at the locations studied. Locations 1 to 11 are along the eastern Arabian Sea and locations 12–19 are along the western Bay of Bengal.

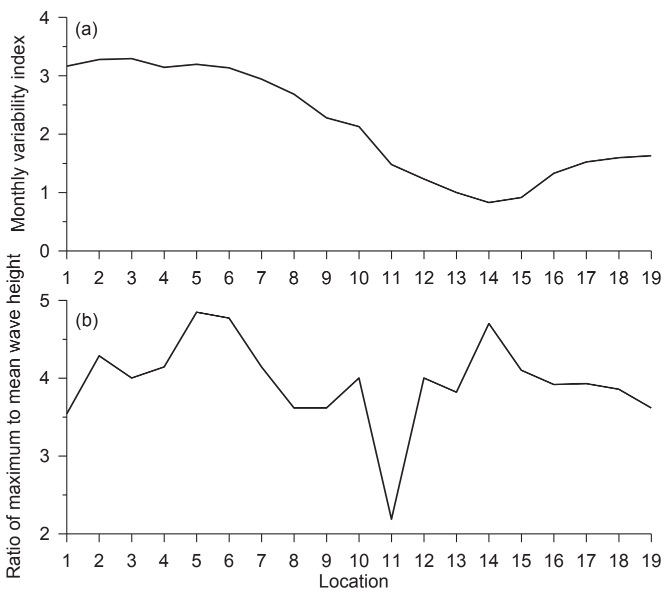


**Fig. 7.** Variation of (a) monthly variability index and (b) ratio of maximum to mean wave height.

monsoon at all of the locations except Location 12 (Fig. 8). At Location 12, the highest seasonal mean wave power occurs during the pre-monsoon period. The wave power during the SW monsoon is 70–77% of the annual wave power at Locations 1–7. At the southern locations in the AS (8–11), the wave power during the SW monsoon is 55–71% of the annual wave power (Fig. 8). Kumar et al. [28] found that the mean wave power is high (15.5–19.3 kW/m) during the SW monsoon along the west coast of India. The present study shows that most of the wave power is available during the SW monsoon period when the availability of solar power is less due to cloud cover. Significantly, during the non-monsoon periods, when the wave power is less, the availability of solar power is high. Hence, it would be ideal to build a combined wave and solar power plant.

Glejin et al. [36] reported that the wave height increases from south to north along the central west coast of India during the SW monsoon period with the average significant wave height measuring 20% more at the northern location than the average significant wave height at the southern location. This difference is due to the increased swell and wind-sea height at the northern location. The present study indicates that the increase in the wave power from Locations 4–7 is only 9% during the SW monsoon period.

During the pre-monsoon period, the wave power is 12–22% of the annual wave power with higher values at the southern locations. The wave power during the post-monsoon period is 9–21% of the annual wave power, and thus, it is slightly less than the wave power during the pre-monsoon period. In the AS, during the pre-monsoon period, the wave power is also higher at the southern locations than at the northern location. The strong seasonality observed in the wave power is similar to the variations observed in significant wave height along the eastern AS [24,25,37]. At Locations 12–15, the lowest seasonal mean wave power occurs during the post-monsoon period, while at other locations, it occurs during the pre-monsoon period.

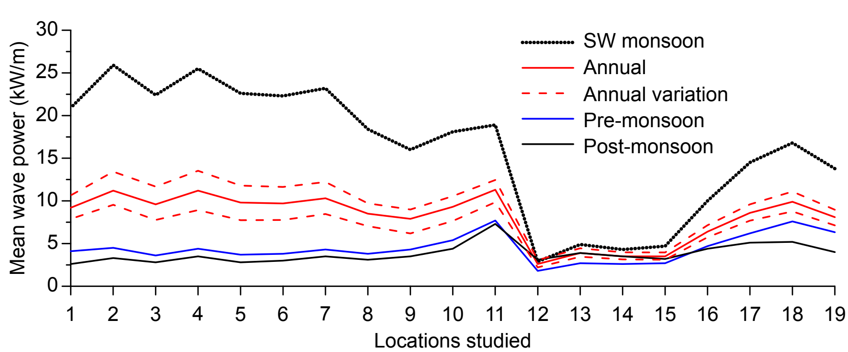


**Fig. 8.** Seasonal and annual mean wave power in the Indian shelf seas. Locations 1–11 are in the AS and locations 12–19 are in BoB.

### 3.4. Annual variations in wave power

Even though the wave power during the SW monsoon is less at the southern location (Location 11), the annual mean wave power is highest (11.3 kW/m) at this location since the wave power during the pre- and post-monsoon periods is highest at this location (Fig. 8). The mean wave power potential for the southwest coast of India near Thiruvananthapuram is 13 kW/m [26]. The annual mean $H_s$ and $T_e$ are maximum (1.6 m and 8.5 s) at Location 11 compared to the other locations studied. Hence, the annual mean wave power is highest at this location. The lowest annual mean wave power along the western shelf seas is at Location 9 (7.9 kW/m). The mean wave power at Locations 2 and 3 during June to August is 29 kW/m and is close to the mean wave power (≈28 kW/m) off Muldwarka in the northern Arabian Sea, which was measured at a water depth of 10 m during June to August [34]. Table 2 shows the percentage of time during an annual cycle that wave power is available in a different range at all locations in the western shelf seas. The table shows that, at all of the locations, wave power between 5 and 10 kW/m is available 12% (Locations 3 and 5) to 38% (Location 11) in a year. Fifty percent of the time, the wave power is more than 8.8 kW/m at Location 11. At Locations 1–9, the wave power is more than 4 kW/m. The wave power is more than 10 kW/m during 25% (Location 8) to 43% (Location 11) of a year.

In the western BoB, the annual mean wave power increases from south to north with the lowest (2.6 kW/m) wave power recorded at the southern location and the highest (9.9 kW/m) at Location 18 (Fig. 8). At Location 19, the annual mean wave power is 8.1 kW/m. Most of the time (>80%), the wave power is less than 5 kW/m (Table 3) at 3 locations (Locations 12, 14 and 15). Fifty percent of the time, the wave power is more than 3 kW/m at Locations 13–15 and more than 6 kW/m at Locations 17–19. More than 25% of the time, the wave power ranges between 5 and 10 kW/m at Locations 16–19 and it is more than 10 kW/m for 28% of the time at Locations 17–19.

The mean annual wave power along the western BoB (2.6–9.9 kW/m) is lower than that available along the eastern BoB (7.9–11.3 kW/m). The annual mean wave power is highest (20–70 kW/m or higher) in the temperate zones (30–60° north and south latitude) where strong storms occur [38]. In the southern hemisphere, the maximum annual mean wave power is ~125 kW/m southwest of Australia near 48°S, 94°E. In the northern hemisphere, the annual mean wave power south of Iceland exceeds 80 kW/m around 56°N, 19°W [38]. The wave energy resource assessment for the Indian shelf seas is calculated by considering the length of coastline that corresponds to each location studied. The estimated total annual mean wave power available is around 19.5 GW (171 TWh/y) along the western shelf seas of India and around 8.7 GW (75.5 TWh/y) along the eastern shelf seas.

The ratio of the maximum wave height to the mean wave height is a rough measure for the feasibility of the energy project [38]. The maximum wave height determines the investment cost and the mean wave height indicates the annual mean wave power availability. The ratio of the maximum wave height to the mean wave height is more than 4.5 at Locations 5, 6 and 14 (Fig. 7b). The ratio of the maximum wave height to the mean wave height is more than 3.5 at all locations except Location 11, where it is 2.2.

**Table 2**
Percentage of time the wave power available in different range for locations along the western shelf seas.

| Location | Position | Wave power (kW/m) | Average $H_s$ (m) | Average $T_e$ (s) | Average wave power (kW/m) | Frequency (%) |
|---|---|---|---|---|---|---|
| 1 | 22.50° N | <5 | 0.83 | 6.83 | 2.43 | 57.65 |
| | 68.25° E | 5–10 | 1.39 | 7.34 | 6.95 | 14.04 |
| | | >10 | 2.34 | 8.53 | 24.16 | 28.32 |
| 2 | 21.00° N | <5 | 0.87 | 7.36 | 2.83 | 54.19 |
| | 69.00° E | 5–10 | 1.32 | 8.09 | 6.85 | 16.13 |
| | | >10 | 2.49 | 8.94 | 28.96 | 29.68 |
| 3 | 19.50° N | <5 | 0.87 | 6.99 | 2.64 | 61.23 |
| | 71.25° E | 5–10 | 1.34 | 7.73 | 6.82 | 12.34 |
| | | >10 | 2.45 | 8.67 | 27.14 | 26.43 |
| 4 | 18.00° N | <5 | 0.91 | 7.37 | 3.05 | 54.89 |
| | 72.00° E | 5–10 | 1.29 | 8.35 | 6.75 | 17.31 |
| | | >10 | 2.51 | 9.01 | 29.89 | 27.80 |
| 5 | 16.50° N | <5 | 0.86 | 7.45 | 2.73 | 60.91 |
| | 72.75° E | 5–10 | 1.28 | 8.34 | 6.73 | 12.97 |
| | | >10 | 2.42 | 9.04 | 27.67 | 26.12 |
| 6 | 15.00° N | <5 | 0.85 | 7.69 | 2.80 | 61.05 |
| | 73.50° E | 5–10 | 1.28 | 8.39 | 6.72 | 12.79 |
| | | >10 | 2.40 | 9.04 | 27.29 | 26.16 |
| 7 | 13.50° N | <5 | 0.89 | 7.91 | 3.08 | 55.64 |
| | 73.50° E | 5–10 | 1.27 | 8.58 | 6.75 | 16.98 |
| | | >10 | 2.40 | 9.02 | 27.33 | 27.39 |
| 8 | 12.00° N | <5 | 0.85 | 8.02 | 2.89 | 59.80 |
| | 74.25° E | 5–10 | 1.29 | 8.33 | 6.84 | 14.69 |
| | | >10 | 2.22 | 8.79 | 22.43 | 25.51 |
| 9 | 10.50° N | <5 | 0.86 | 8.20 | 3.04 | 54.57 |
| | 75.00° E | 5–10 | 1.29 | 8.55 | 6.95 | 19.47 |
| | | >10 | 2.07 | 8.73 | 18.98 | 25.96 |
| 10 | 09.00° N | <5 | 0.87 | 8.59 | 3.22 | 44.66 |
| | 75.75° E | 5–10 | 1.27 | 8.88 | 7.02 | 24.18 |
| | | >10 | 2.07 | 9.00 | 19.72 | 31.16 |
| 11 | 07.50° N | <5 | 1.00 | 8.05 | 3.93 | 17.73 |
| | 77.25° E | 5–10 | 1.33 | 8.29 | 7.14 | 38.64 |
| | | >10 | 2.02 | 8.80 | 18.07 | 43.63 |

**Table 3**
Percentage of time the wave power available in different range for locations along the eastern shelf seas.

| Location | Location | Wave power (kW/m) | Average $H_s$ (m) | Average $T_e$ (s) | Average wave power (kW/m) | Frequency (%) |
|---|---|---|---|---|---|---|
| 12 | 10.50° N | <5 | 0.83 | 5.87 | 2.10 | 90.14 |
| | 81.00° E | 5–10 | 1.47 | 6.07 | 6.46 | 8.85 |
| | | >10 | 2.01 | 6.80 | 13.76 | 1.01 |
| 13 | 12.00° N | <5 | 0.93 | 6.32 | 2.76 | 76.59 |
| | 81.00° E | 5–10 | 1.44 | 6.50 | 6.60 | 20.76 |
| | | >10 | 2.00 | 6.87 | 13.80 | 2.64 |
| 14 | 13.50° N | <5 | 0.92 | 6.42 | 2.73 | 82.69 |
| | 81.00° E | 5–10 | 1.38 | 6.88 | 6.40 | 15.86 |
| | | >10 | 2.00 | 7.31 | 14.94 | 1.45 |
| 15 | 15.00° N | <5 | 0.90 | 6.46 | 2.66 | 81.51 |
| | 81.00° E | 5–10 | 1.41 | 6.73 | 6.53 | 16.51 |
| | | >10 | 2.07 | 6.95 | 15.28 | 1.98 |
| 16 | 16.50° N | <5 | 0.90 | 7.52 | 3.07 | 49.50 |
| | 83.00° E | 5–10 | 1.36 | 7.86 | 7.13 | 33.84 |
| | | >10 | 1.91 | 8.05 | 14.70 | 16.65 |
| 17 | 18.84° N | <5 | 0.91 | 7.88 | 3.24 | 38.15 |
| | 85.00° E | 5–10 | 1.34 | 8.24 | 7.18 | 31.69 |
| | | >10 | 2.00 | 8.40 | 16.93 | 30.16 |
| 18 | 19.50° N | <5 | 0.87 | 8.37 | 3.16 | 33.98 |
| | 87.00° E | 5–10 | 1.32 | 8.66 | 7.26 | 29.50 |
| | | >10 | 2.02 | 8.84 | 18.23 | 36.51 |
| 19 | 21.00° N | <5 | 0.81 | 8.72 | 2.85 | 42.87 |
| | 88.50° E | 5–10 | 1.30 | 8.85 | 7.29 | 28.74 |
| | | >10 | 1.92 | 8.97 | 16.75 | 28.39 |

### 3.5. Inter-annual variations in wave power

Many studies indicate inter-annual variations in wave climate [39,40]. Hence, inter-annual variations in wave power are studied to ensure stable wave energy. The study shows that, in the western shelf seas of India, the inter-annual variations in annual mean wave power are 12–20% and the higher variations occur at Locations 3–5 (Fig. 9). The annual mean wave power along the eastern AS show an increasing trend and vary from 0.016 kW/m/y (Location 8) to 0.053 kW/m/y (Location 3).

The inter-annual variations in wave power along the eastern shelf seas are 10–15% of the mean annual values at different locations (Fig. 10). The annual mean wave power along the western BoB show an increasing trend (0.002–0.034 kW/m/y) at all locations except Location 15, which shows a negligible decreasing trend (−0.002 kW/m/y).

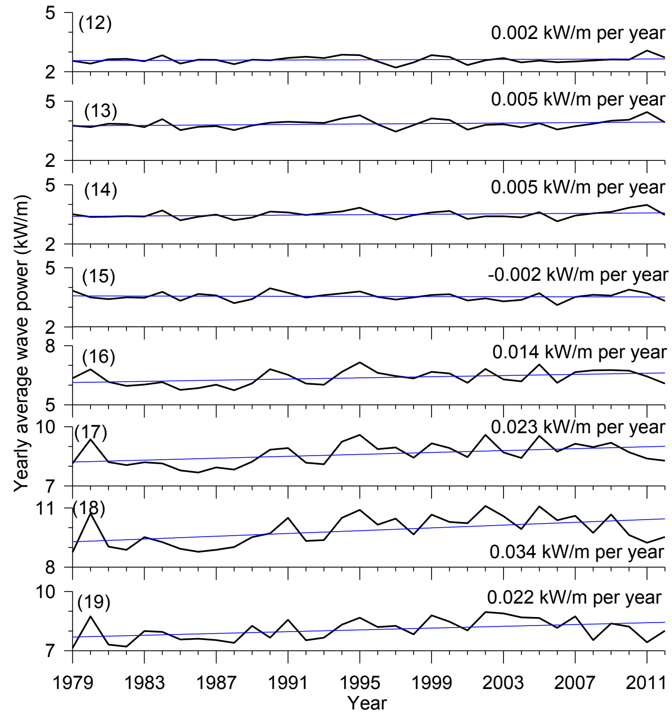


**Fig. 10.** Variation of yearly mean wave power along the western Bay of Bengal.

## 4. Conclusions

This study used the 34-year (January 1, 1979 to December 31, 2012) ERA-I dataset produced by the ECMWF to examine the temporal and spatial variability of the wave power along the shelf seas of India. Along the western shelf seas of India, the mean wave power during June–August measures more than 20 kW/m. At all locations, the monthly mean wave power is highest during July followed by June. The trends of the annual mean wave power show an increasing trend (0.002–0.053 kW/m/y) at all locations except Location 15. The mean annual wave power along the western BoB (2.6–9.9 kW/m) is lower than the mean annual wave power available along the eastern AS (7.9–11.3 kW/m). The total annual mean wave power available along the western shelf seas of India is around 19.5 GW, and the total annual mean wave power available along the eastern shelf seas is around 8.7 GW. The monthly variability index indicates that the wave power variability is more at Locations 1–7 along the western shelf seas and less at Locations 11–17. The wave power is more than 10 kW/m during 43% of the time in a year at Location 11 and the mean wave power also is the highest [11.3 kW/m] at this location compared to the other locations studied in the Indian shelf seas. The relatively low value of the ratio of the maximum to mean wave height and the high annual mean wave power at Location 11 makes this location suitable for installation of a wave energy plant.

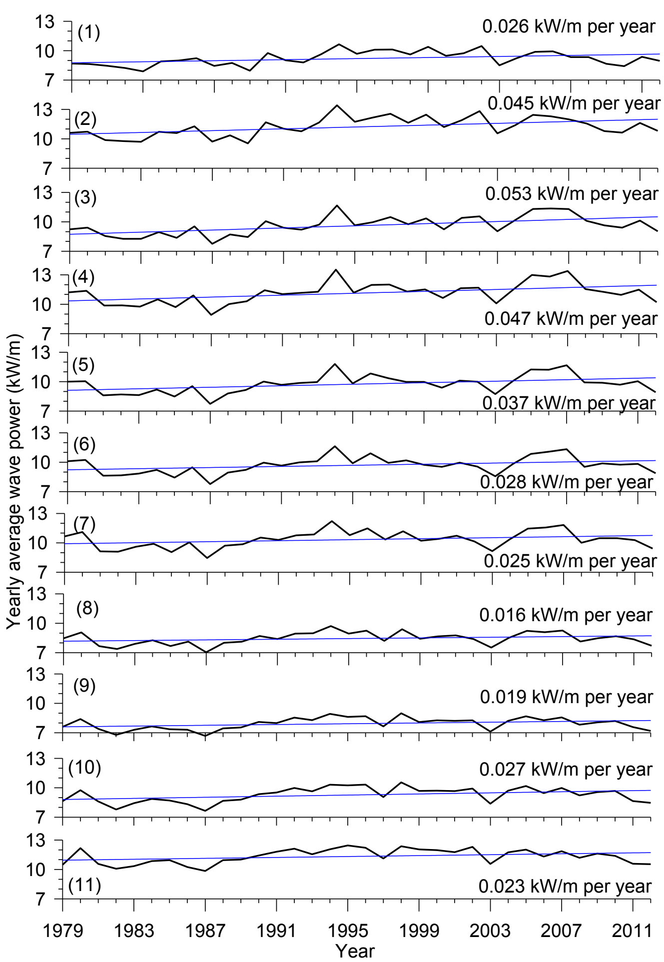


**Fig. 9.** Variation of yearly mean wave power along the eastern Arabian Sea.


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## References


[1] Clement, McCullen P, Falcao A, Fiorentino A, Gardner F, Hammarlund K. Wave energy Europe: current status and perspectives. Renew Sustain Energy Rev 2002;6-5:405–31.
[2] Neill SP, Hashemi MR. Wave power variability over the northwest European shelf seas. Appl Energy 2013;106:31–46.
[3] Akpinar A, Komurcu MI. Assessment of wave energy resource of the Black sea based on 15-year numerical hindcast data. Appl Energy 2013;101:502–12.
[4] Bernhoff H, Sjostedt E, Leijon M. Wave energy resources in sheltered sea areas: a case study of the Baltic Sea. Renew Energy 2006;31:2164–70.
[5] Stopa JE, Filipot JF, Li N, Cheung KF, Chen YL, Vega L. Wave energy resources along the Hawaiian Island chain. Renew Energy 2013;55:305–21.
[6] Kamranzad B, Etemad-shahidi A, Chegini V. Assessment of wave energy variation in the Persian Gulf. Ocean Eng 2013;70:72–80.
[7] Hughes MG, Heap AD. National-scale wave energy resource assessment for Australia. Renew Energy 2010;35:1783–91.
[8] Dunnett D, Wallace JS. Electricity generation from wave power in Canada. Renew Energy 2009;34:179–95.
[9] Wilson J, Beyene A. California wave energy resource evaluation. J Coast Res 2007;23(3):679–90.
[10] Iglesias G, Carballo R. Wave resource in El Hierro – an island towards energy self-sufficiency. Renew Energy 2011;36:689–98.
[11] Zheng CW, Zhuang H, Li X, Li XQ. Wind energy and wave energy resources assessment in the East China Sea and South China Sea. Sci China – Technol Sci 2012;55:163–73.

[12] Sierra JP, González-Marco D, Sospedra J, Gironella X, Mösso C, Sánchez-Arcilla A. Wave energy resource assessment in Lanzarote (Spain). Renew Energy 2013;55:480–9.
[13] Abbaspour M, Rahimi R. Iran atlas of offshore renewable energies. Renew Energy 2011;36:388–98.
[14] ESBI Environmental Services. Accessible Wave Energy Resource Atlas: Ireland: Report No. 4D404A-R2 prepared for the Marine Institute/Sustainable Energy Ireland. 2005.
[15] Wan Nik WB, Sulaiman OO, Rosliza R, Prawoto Y, Muzathik AM. Wave energy resource assessment and review of the technologies. Int J Energy Environ 2011;2(6):1101–12.
[16] Rusu E, Guedes Soares C. Numerical modelling to estimate the spatial distribution of the wave energy in the Portuguese nearshore. Renew Energy 2009;34:1501–16.
[17] Mota P, Pinto JP. Wave energy potential along the western Portuguese coast. Renew Energy 2014;71:8–17.
[18] Chiu FC, Huang WY, Tiao WC. The spatial and temporal characteristics of the wave energy resources around Taiwan. Renew Energy 2013;52:218–21.
[19] ABP Marine Environmental Research Ltd (ABP). Atlas of UK Marine Renewable Energy Resources: Technical Report, Report No.R.1106 prepared for the UK Department of Trade and Industry. 2004.
[20] Defne Z, Haas KA, Fritz HM. Wave power potential along the Atlantic coast of the southeastern USA. Renew Energy 2009;34:2197–205.
[21] Lenee-Bluhm P, Paasch R, Özkan-Haller HT. Characterizing the wave energy resource of the US Pacific Northwest. Renew Energy 2011;36:2106–19.
[22] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012;44:296–304.
[23] Arinaga RA, Cheung KF. Atlas of global wave energy from 10 years of reanalysis and hindcast data. Renew Energy 2012;39:49–64.
[24] Glejin J, Kumar VS, Nair TMB, Singh J. Influence of winds on temporally varying short and long period gravity waves in the near shore regions of eastern Arabian Sea. Ocean Sci 2013;9:3021–47.
[25] Sajiv PC, Kumar VS, Glejin J, Dora GU, Vinayaraj P. Interannual and seasonal variations in near shore wave characteristics off Honnavar, west coast of India. Curr Sci India 2012;103:286–92.
[26] Ravindran M, Koola PM. Energy from sea waves – the Indian wave energy programme. Curr Sci India 1991;60(12):676–7.
[27] Mala K, Jayaraj J, Jayashankar V, Muruganandam TM, Santhakumar S, Ravindran M, et al. A twin unidirectional impulse turbine topology for OWC based wave energy plants – experimental validation and scaling. Renew Energy 2011;36:307–14.
[28] Kumar VS, Dubhashi KK, Nair TMB, Singh J. Wave power potential at few shallow water locations around Indian coast. Curr Sci India 2013;104(9):1219–24.
[29] Dee DP, Uppala SM, Simmons AJ, Berrisford P, Poli P, Kobayashi S. The ERA-interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc 2011;137:553–97.
[30] Simmons A, Uppala C, Dee D, Kobayashi S. ERA-Interim: new ECMWF reanalysis products from 1989 onwards. ECMWF Newsl 2007;110:25–35.
[31] Komen GJ, Cavaleri L, Doneland M, Hasselmann K, Hasselmann S, Janssen PAEM. Dynamics and modelling of ocean waves. Cambridge University Press; 1994.
[32] Stopa JE, Cheung KF. Intercomparison of wind and wave data from the ECMWF Reanalysis Interim and the NCEP Climate Forecast System Reanalysis. Ocean Model 2014;75:1–19.
[33] Premkumar K, Ravichandran M, Kalsi SR, Sengupta D, Gadgil S. First results from a new observation system over the Indian Seas. Curr Sci India 2000;78:323–30.
[34] Kumar VS, Singh J, Pednekar P, Gowthaman R. Waves in the nearshore waters of northern Arabian Sea during the summer monsoon. Ocean Eng 2011;38(2–3):382–8.
[35] Cornett AM. A global wave energy resource assessment. In: International offshore and polar engineering conference, Vancouver, Canada; 2008. p.318–26.
[36] Glejin J, Kumar VS, Philip SC, Singh J, Pednekar P, Kumar KA, et al. Variations in swells along eastern Arabian Sea during the summer monsoon. Open J Mar Sci 2012;2:43–50.
[37] Kumar VS, Glejin J, Dora GU, Sajiv CP, Singh J, Pednekar P. Variations in nearshore waves along Karnataka, west coast of India. J Earth Syst Sci 2012;121:393–403.
[38] Barstow S, Gunnar M, Mollison D, Cruz J. The wave energy resource. In: Cruz J, editor. Ocean wave energy. Berlin: Springer; 2008. p. 93–132.
[39] Gulev SK, Grigorieva V. Last century changes in ocean wind wave height from global visual wave data. Geophys Res Lett 2004;31:L24302,. http://dx.doi.org/10.1029/2004GL021040.
[40] Shanas PR, Kumar VS. Temporal variations in the wind and wave climate at a location in the eastern Arabian Sea based on ERA-Interim reanalysis data. Nat Hazards Earth Syst Sci 2014;14:1371–81. http://dx.doi.org/10.5194/nhess-14-1371-2014.