Evaluation of spatio-temporal variability of ocean wave power resource around Sri Lanka

Harshinie Karunarathna[1], Pravin Maduwantha[2], Bahareh Kamranzad[3,4], Harsha Rathnasooriya[2], Kasun de Silva[2]

[1]Zienkiewicz Centre for Computational Engineering
College of Engineering
Bay Campus
Swansea University
Swansea SA1 8EN
UK
Email: h.u.karunarathna@swansea.ac.uk
(corresponding author)

[2]Department of Civil Engineering
University of Moratuwa,
Moratuwa
Sri Lanka

[3]Graduate School of Advanced Integrated Studies in Human Survivability (GSAIS)
Kyoto University
Yoshida-Nakaadachi 1
Sakyo-ku, Kyoto 606-8306
Japan

[4]Hakubi Center for Advanced Research
Kyoto University
Yoshida Honmachi
Sakyo-ku, 606-8501
Kyoto
Japan

Abstract

The paper presents a detailed analysis of the spatio-temporal variability of wave power resource around Sri Lanka, using computationally simulated 25 years of wave data that represents the prevailing ocean climate in the region. The computational wave model was validated against a measured wave dataset collected over a 44-month period at 70m water depth off the coast of the south-west of Sri Lanka and compared with ERA-Interim Reanalysis wave data and, good agreement found. The analysis reveals that the ocean around Sri Lanka from the south-west to south-east have a substantial wave power resource. The available offshore wave power resource remains between 10-20 kW/s throughout the year although it is significantly modulated by the south-west monsoon which falls between May and September thus increasing the power up to around 30 kW/m. The inter-annual to decadal scale variability of wave power resource remains small. Wave power reduces when waves travel from the margin of the narrow continental shelf around Sri Lanka to shallow water areas closer to the shoreline. A significant longshore variability of wave power is also observed where the south-west coast of Sri Lanka has the highest available power under the prevailing ocean climate.

Keywords: Wave power, Wave simulations, Sri Lanka, Indian Ocean, South-west tropical monsoon.

1. Introduction

Serious environmental implications associated with energy production using non-green sources and ever-increasing global energy demand have led investigations into exploring the potential to generate energy from renewable resources. Among numerous forms of renewable energy sources, ocean wave energy has been recognised as having one of the highest energy densities worldwide (Leijon et al., 2003). In addition, low environmental implications and minimal or no use of land have made wave energy an option favoured by many countries (Iglesias et al., 2009). As a result, numerous countries bordering coastal seas and oceans have conducted studies to assess and quantify available wave energy resource, which is the primary requirement for planning and implementation of wave energy harvesting projects.

Cornett (2009) carried out a broad-scale study on global wave resource using numerically simulated ocean waves. He presented a range of parameters including the 'energy period' that can be used to describe and quantify the temporal variation of wave energy resource at a given location. He also highlighted the importance of considering the frequency and intensity of extreme wave conditions when evaluating wave energy resource. His study has also been useful to identify regions which have the highest wave energy potential in the world. Liberti et al. (2013) assessed spatial variation of wave energy resource in the Mediterranean Sea using numerically simulated wave data. Their study prompted to identify the areas where wave energy resource is most promising in the Mediterranean. Kamranzad et al (2013) assessed wave power variation in the Persian Gulf while Kamranzad et al. (2016) evaluated wave energy resource in the Southern Caspian Sea. They investigated temporal as well as spatial variation of wave power resource in that region, thus allowing them to identify wave energy hotspots and the stability of the source over time. Liang et al. (2013) carried out a spatio-temporal wave energy resource evaluation in a small coastal area in China using numerically simulated wave data for a period of 16 years, focusing mostly on the areas close to the shoreline. Similar analysis has been carried out by Goncalves et al. (2014) around the Canary Islands, using simulated wave data over a period of 30 years. They determined the spatial spread of the power resource and, also calculated the probability of occurrence of different sea states. Robertson et al (2014) investigated the nearshore wave resource on the west coast of Vancouver Island, Canada using waves simulated by SWAN wave model. They concluded that the reduced directional frequency spread of waves in the nearshore may make nearshore energy harvesting more attractive. Mirzaei et al. (2014) assessed wave energy potential along the east coast of Malaysia using simulated waves over a period of 31 years since 1979. They investigated the seasonal and inter-annual variation of the resource and established a correlation between wave power fluctuation and local climate variabilities. Neill et al. (2017) assessed both wave and tidal resource of Scotland. They concluded that more consistent, less energetic sites should also be considered alongside high energy sites for future developments as they can partially offset the inter-annual variability of the energy resource. Sierra et al. (2017) assessed intra-annual and inter-annual variability of wave energy resource in the Bay of Biscay, France. Their results have shown that average wave power alone is insufficient to quantify available wave power and that intra-annual and inter-annual variations need to be investigated. Lin et al (2019) assessed the wave energy resource around China with the aid of a 20-year wave simulation using SWAN wave model. The spatial and temporal variation of wave energy are noted and most favourable areas for potential future wave energy developments around Chinese seas were identified. Similar other studies have been carried out in numerous other countries around the world, who are interested in investigating wave energy harvesting potential (e.g. Folley and Whittaker, 2009 - UK; Iglesias et al., 2009 – Spain; Bernhoff et al., 2006 – Sweden; Iglesias and Carballo, 2010 – France; Hughes and Heap, 2010, Morim et al., 2016 and, Hemer et al., 2017 – Australia; Alonso et al., 2017- Uruguay, Kopor et al., 2018 – Thailand and, some others).

Studies on wave power resource in the Indian Ocean are rare, except for regional studies focusing mainly on coastal areas of India (Aboobacker, 2017; Zheng and Li, 2017; Sannasiraj and Sundar, 2016) and Iran (Kamranzad et al., 2016; Saket and Etemad-Shahidi, 2012). In a recent study, Kamranzad and Mori (2019) introduced a new identifier to specify areas with higher stability of wave power, considering both short-term fluctuations (months) and long-term changes due to global climate variabilities. The application of the identifier to the Indian Ocean suggested that the south-western to south-eastern coastal areas of Sri Lanka have a high energy potential and stability in both short and long-term, although the resolution of the data used is not adequate to carry out a detailed analysis.

Sri Lanka, being an island located in the Indian Ocean, is exposed to energetic wave conditions all year round thus making wave energy a potential renewable energy resource to supplement country's ever-growing demand for green energy. Sustainable Energy Authority of Sri Lanka, who is responsible for strategic planning of future green energy and the Ceylon Electricity Board of Sri Lanka who supplies and manages electricity to the country, have identified wave energy as a potential resource which needs detailed investigations. Chamara and Vithana (2018) analysed nearshore wave power resource along the south-west and south coasts of Sri Lanka using a numerical model forced by a measured set of offshore waves (Sheffer et al., 1994). Their analysis was limited to a very short period of time and also to one sea bed contour. As a result, they were unable to determine spatial and temporal variability and stability of the resource. Amarasekera et al. (2014) carried out a feasibility study of ocean wave power in the south coast of Sri Lanka using numerically simulated waves from the WAVEWATCHIII model. They concluded that installation of small-scale wave energy devices can be feasible. However, it is not clear if swell waves were taken into account in their analysis.

Wave energy may be captured either at nearshore or at offshore locations, depending on the available technology, energy demand, the scale of the preferred development, budgetary constraints and the infrastructure required for grid connections. It also depends on social and environmental constraints. As waves travel from the deep sea to nearshore areas, available wave power can vary as a result of numerous wave transformation processes such as shoaling, refraction, diffraction and dissipation associated with the variability of sea bottom bathymetry. Wave power resource also vary over time due to seasonal weather patterns, regional climatic variations and global climate change in the long term. A recent study has revealed that due to temporal variations, the areas containing higher wave energy may not necessarily be the optimal locations for energy harvesting (Besio et al., 2016). Hence, it is vital to take into account the temporal variability of the wave energy resource when selecting locations appropriate for wave energy harvesting.

The focus of the current study was (i) to evaluate the spatial distribution of wave power resource around Sri Lanka in order to identify wave power hotspots. This analysis is important for selecting sites suitable for future energy developments; (ii) to quantify the available wave power resource along the coast considering both nearshore and offshore wave conditions. This is important for making decisions relating to the scale and nature of future wave energy harvesting projects and selecting devices; and (iii) To investigate the temporal variation of the energy resource over a range of timescales. This is essential for evaluating the stability and sustainability of the energy resource over a range of timescales. Numerically simulated ocean waves over a period of 25 years were used for this analysis.

2. The study area

Sri Lanka is located between 5°-10°N north of the equator and between 79°-82°E longitude, in the northern Indian Ocean. The country is surrounded by a very narrow continental shelf. The shallow shelf in the north separates the island from India. The width of the continental shelf varies between 5 km to 25 km where the narrowest shelf is found off the coast of Dondra, a location about 15 km to the east of Matara. The water depth sharply increases beyond the edge of the continental shelf, reaching more than 1000m within a very short distance (Fig. 1). The coastline of Sri Lanka consists of numerous complex features including long sandy beaches, semi-enclosed bays and lagoons, river inlets, rocky headlands and coastal wetlands. The ocean wave climate in the south-west to south east coastline is characterised by long distance swell waves. However, tropical monsoon systems operating in the Indian Ocean seasonally modulates the wave climate. The south-west monsoon, which operates between May and September generates energetic sea waves along the west, south-west and south coasts of Sri Lanka. The north-east monsoon generates high sea waves in the north and east between December and February (Coast Conservation Department, 1997).

Location of Fig. 1

Fig. 1: (a) Map of Sri Lanka and its location in the Indian Ocean; (b) Sea bed contours around Sri Lanka showing the narrow continental shelf with a steep slope.

Some wave measurements have been reported at two locations around Sri Lanka: Coast Conservation and Coastal Resources Department of Sri Lanka (CCD), with the cooperation of the German Agency for Technical Corporation (GTZ) has carried out a continuous wave measurement programme off the coast of Galle (Fig. 1), at a water depth of 70m, over a period of 3.5 years between 1989 and 1991. Waves were measured using a DATAWELL B.V. directional wave buoy (Fig. 4b, GM) for 30 minutes duration every three hours. Waves at the measurement location are assumed to be representative of the wave climate in the south-west of Sri Lanka (Sheffer et al., 1994). Those measurements concluded that long-distance swell waves occupied a significant proportion of incident wave energy spectrum. A sample measurement of sea and swell wave conditions is given in Fig. 2a, which shows a clear seasonal variability where highly energetic seas prevail during the south-west monsoon between May and September. The magnitude of significant swell wave heights varies between 0.5m to 2.5 m while that of sea waves vary from 0.2m to 3.0 m during the measurement period. On average, sea waves have wave periods around 4 s and swell waves have periods around 11 sec. Swell wave roses determined from the measurements (Fig. 2b) show that the predominant swell wave approach direction is from the south. The wave measurement procedure and an analysis of the wave climate of the south-west of Sri Lanka can be found in Sheffer et al., (1994).

Location of Fig. 2a and Fig. 2b

Fig. 2a: A selection of measured sea/swell wave height (top) and period (bottom) time series offshore of Galle.

Fig. 2b: Swell wave height roses determine from waves measured off Galle of the south-west coast of Sri Lanka over a period of 3 years between 1989 and 1992.

Recently, wave measurements have been carried out at two locations off the coast of Matara, located in the south coast of Sri Lanka (Fig. 1) at 20 m (non-directional Buoy 1) and 10 m

(Buoy 2) water depths (http://www.sciencedb.cn/dataSet/handle/447) (Fig. 4b, MM1 and MM2 respectively). The measurements contain wave time series (significant wave height and corresponding wave period) at the two water depths for a period of five months (Sept. 2013 – Feb. 2014) at Buoy 1 and of 12 months (April 2013 – April 2014) at Buoy 2. Buoy 1 has collected data continuously and the data for every 10 minutes have been processed as one record. Buoy 2 has collected 15-minute samples every 1 hour from which significant wave conditions have been derived. Concurrent wind records have also been collected at an automated weather station at a nearby seaside land point. Measured wave conditions are shown in Fig. 3a. Those data have been used to determine monthly percentage sea and swell wave conditions and has found that swell wave component is greater than 57% all throughout the year and reached 77% in November 2013. A seasonal signal similar to Galle measured data (Fig. 2) can be seen where south-west monsoon between May and September brings larger waves to the south coast. The average significant wave height during the south-west monsoon is found to be1.5 m while that outside monsoon period is around 1.0 m. The average wave period is around 9.0 s. Wave height roses for Matara Buoy 2 data are shown in Fig. 3b. The predominant wave approach direction has been identified as the south, except from December to March where a significant proportion of waves approach from the south-east. It should be noted that considerable local effects can be expected on wave heights and directions at measured at buoy 2, which is located at a shallow 10 m water depth. A detailed description of the measurement programme, results and analysis can be found in Luo et al. (2018).

Location of Fig. 3a and Fig. 3b

Fig 3a: Time series of measured significant wave height (top) and period (bottom) from Matara Buoy 1 (red) and Buoy 2 (blue).

Fig. 3b - Significant wave height roses determine from waves measured at Matara wave boy 2 during April 2013 – April 2014.

Thevasiyani and Perera (2014) have carried out an extreme wave analysis of Galle wave measurements given in Sheffer et al. (1994). They have separated extreme wave conditions using peak-over-threshold method and fitted them to Generalised Pareto Distribution to determine statistically significant extreme sea and swell conditions. They concluded that most energetic seas occur during the south-west monsoon season. The 5, 50 and 100 year return period significant sea wave heights during the south-west monsoon were found to be 4.12 m, 5.22 m and 5.58 m respectively and that of swell waves were 2.82 m, 3.00 m and 3.03 m respectively.

Gunaratna et al. (2011) investigated the nearshore spatial variability of wave climate along the south coast of Sri Lanka through a numerical modelling study based on MIKE 21 SW modelling software (https://www.mikepoweredbydhi.com/products/mike-21/waves). They highlighted the significance of wave transformation processes that take place when waves travel from the offshore to shallow water.

3. Sri Lanka wave model and model validation

3.1 The wave model

To determine detailed wave climate around Sri Lanka, which will be the basis of wave energy characterisation, long term ocean waves were derived from a large scale Indian Ocean wave model (KU_IO) (Kamranzad and Mori, 2019), developed using SWAN spectral wave modelling software (Booji et al., 1999). The KU_IO model domain covers the area between 71°S-30°N in latitude and 20°E-90°E in longitude. The spatial resolution of the model is 0.5°×0.5°. The wind input for the KU_IO model is taken from the Japan Meteorological Agency super-high-resolution global climate model MRI-AGCM3.2S (Mizuta et al. 2012). Wind inputs were available for a period of 25 years from 1979 to 2003, covering the 'current' climate conditions. The spatial and temporal resolution of wind inputs were 20 km and 1 hr, respectively. The wind source term in SWAN is calculated using those wind outputs, following Komen et al. (1984). Non-nonlinear quadruplet wave interaction formulation of Hasselmann et al. (1985) was used. Further details of model development and adopted wave transformation processes can be found in the Booji et al., 1999. The frequency domain of the model consists of frequencies from 0.03 to 1 Hz with 36 bins on a logarithmic scale. The directional computational grid was divided into 36 bins of 10°. The KU_IO model has been extensively validated using numerous satellite derived wave data (Kamranzad and Mori, 2019). Although the resolution of the KU_IO model outputs were not sufficient for a detailed wave power resource analysis, they provided useful information relating to the most desirable areas around Sri Lanka for wave energy harvesting.

In this study, two high resolution wave models, (i) India regional wave model (64°E-90°E and 0-26°N); and (ii) Sri Lanka regional wave model (5°-11°N, 79.5°-83.5°E), were set up using SWAN, which determined wave and wind boundary conditions from the KU_IO model, to establish high resolution wave climate around Sri Lanka. The KU_IO and the two regional model domains are shown in Fig. 4a. The India regional wave model has the spatial resolution of 0.166° while Sri Lanka regional model has the resolution of 0.05°. GEBCO seabed bathymetry data with 30 arc-second spatial resolution was used in all model domains. The SWAN spectral wave model has been extensively used for wave simulations and wave power resource assessments worldwide (e.g. Liang et al., 2013; Robertson et al., 2014; Kamranzad et al., 2016; Kompor et al., 2018; Lin et al, 2019). The models were then used to generate wave climate around Sri Lanka for 25 years between 1979 and 2003 at 6 hr intervals.

Location of Fig. 4

Fig. 4: (a) Indian Ocean KU_IO and local wave model domains used for wave projections for the Sri Lanka region and (b) Measured, modelled and ERA Interim wave data locations used for wave model validation. GM - Galle (Measured), GE - Galle (ERA-Interim), GMO – Galle (Modelled). P1 and P2 are additional model validation points.

3.2 Wave model validation

Although the KU_IO model, which provided boundary conditions for the Sri Lanka regional model has been extensively validated, the Sri Lanka regional model was validated against two data sources before being used for simulating long term wave data. The first source is the measured wave data at Galle (5.93 N 80.23 E) between 1989 and 1991 using a DATAWELL B.V. directional wave buoy. Waves have been measured for 30 minutes duration every three hours, by the Coast Conservation and Coastal Resources Department of Sri Lanka, in collaboration with the German Agency for Technical Corporation (GTZ) (Sheffer et al., 1994). The second source is the ERA-Interim Global Atmospheric Reanalysis wave data produced by the European Centre for Medium-range Weather Forecasts (ECMWF) (https://apps.ecmwf.int/datasets/). Modelled and ERA-Interim Reanalysis wave data at the closet available Galle wave measurements location and two more locations around the west and south coasts of Sri Lanka were selected for comparisons. Locations of the measured and

ERA Interim Reanalysis data used for model validation are summarised in Figure 4b and Table 1.

Table 1: Details of all data locations used for wave model validation

Details of Data Sets		Location	Duration	Frequency
Galle	**Measured**	**5.93 N, 80.23 E**	**1/2/1989 – 19/9/1992**	**3hr**
	Modelled	5.9313N, 80.2324E	1/2/1989 – 19/9/1992	6hr
	ERA-Interim	6.000N, 80.250E	1/2/1989 – 19/9/1992	6hr
P1	Modelled	6.750N, 79.750E	1/1/1999 – 31/12/2003	6hr
	ERA-Interim	6.750N, 79.750E	1/1/1999 – 31/12/2003	6hr
P2	Modelled	6.250N, 81.750E	1/1/1999 – 31/12/2003	6hr
	ERA-Interim	6.250N, 81.750E	1/1/1999 – 31/12/2003	6hr

Fig. 5a gives a direct comparison between measured (at Galle - GE in Fig. 4b) and modelled (at GMO in Fig. 4a) significant wave height time series for the period of 44-months between 1989 and 1992. The model was able to accurately reproduce the significant wave heights and their temporal variations at this location during this time period although some extreme wave events have not been reproduced satisfactorily. This may be due to the model not being able to capture some locally generated high energy events, potentially as a result of the selected resolution and the wind forcing used.

A comparison of monthly averaged modelled, measured and ERA-Interim Reanalysis significant wave heights during the same time period is shown in Fig. 5b. These results reveal that the measured and modelled monthly averaged significant wave heights at Galle are well in agreement [Root Mean Square Error (RMSE) = 0.12m] except in January and February where the model predictions are slightly higher. ERA-Interim Reanalysis monthly averaged wave heights between July and September are smaller than those measured and modelled but are in agreement in all other months. The RMSE between modelled and ERA-Interim Reanalysis and modelled monthly averaged wave heights is 0.15m. The modelled measured and ERA Interim Reanalysis monthly averaged mean wave period T_{m02} (=$\sqrt{m_0/m_2}$ where m_0 and m_2 are the zeroth and the second moment of the wave frequency spectrum) are compared in Fig. 5c. Modelled T_{m02} from June to August are significantly lower (maximum of 35%) than the measured values although they are comparable during the rest of the year. It is well established that SWAN wave model underestimates the mean and peak wave periods by 10%-20% (SWAN Team, 2017). The sensitivity of T_{m02} to very high frequency waves should also be noted. The model may not capture very high frequency wind sea conditions that dominate the local wave climate during the south-west monsoon season. However, it is worth mentioning that waves with very high frequencies are not important to wave energy resource studies as most extractable energy is concentrated at lower frequencies. ERA-Interim T_{m02} wave periods are significantly higher than both measured and modelled wave periods except in the months June, July and August.

Location of Fig. 5

Fig. 5: Comparison of modelled [at GMO, (5.93° N 80.23° E)] (green), ERA-Interim Reanalysis [at GE (6.0N, 80.250E) (yellow) and measured [at GM (5.93 N, 80.23E)] (red) waves. (a) wave height time series; (b) Monthly averaged significant wave height; and (c) Monthly averaged wave period (T_{m02} for GM and GMO, mean period for GE). Monthly averaging is done taking the data for the period of 1989-1992.

The spectral densities S_f (m^2/Hz) and direction of the modelled waves at location 80°21'E, 5°54'N (the closest model grid point to Galle wave buoy) at different times of the year 2000 are shown in Fig. 6. A significant proportion of long period swell waves van be found in May and July 2000, which falls within the tropical south-west monsoon period. The wave spectral density is significantly smaller outside the monsoon period. The modelled wave frequency spectra are in very good qualitative agreement with the measured spectra at Galle (Figures 1.11 to 1.13 -Sheffer et al. 1994). Due to unavailability of measured data in digital form, we are unable to perform a quantitative comparison of measured and modelled wave spectra.

Location of Figure 6

Figure 6 – A selection of modelled wave spectral densities S_f (m^2/Hz) against frequency f (Hz) in year 2000 at a model grid point (80°21'E, 5°54'N), located closest to the Galle wave buoy location.

To supplement wave model validation against measured data at Galle, modelled waves at two other locations (P1, P2 - Fig. 4a) in the west and south coast of Sri Lanka are compared with ERA-Interim Reanalysis wave data. In Figure 7, a direct comparison of modelled and ERA-Interim Reanalysis significant wave heights at points P1 and P2 is given. The maximum deviation between the two data sets is 1.5m at both locations, except for a small number of outliers found at P1. The gradient of the linear trend lines at P1 and P2 are 0.94 and 1.1 respectively and RMSE between the two datasets at P1 and P2 are 0.4 m and 0.5 m respectively.

Location of Fig. 7.

Fig. 7: A comparison of modelled and ERA-Interim Reanalysis significant wave heights during the period 1999-2003 at points P1 and P2. Black dark line gives x =y line while black dotted lines gives 80% confidence interval. The red dotted line gives the linear fit.

A figure similar to Figure 7 for mean energy period T_{m-10} (Eq. 1) (Schulz-Stellenfleth et al., 2007) is shown in Figure 8. T_{m-10} is selected for making comparison as that is the most appropriate representative wave period for wave power calculations. According to Fig. 6, although the maximum deviation between modelled and ERA-Interim Reanalysis T_{m-10} values are large the gradient of the trend lines at P1 and P2 are 0.92 and 0.91 respectively while RMSE between the two datasets at P1 and P2 are 1.6 s and 1.7 s respectively, which indicates good overall agreement between the two datasets.

$$T_{m-10} = \frac{m_{-1}}{m_0} \qquad (1)$$

in which m_{-1} is the first negative spectral moment and m_0 is the zeroth spectral moment of the wave frequency spectrum.

Location of Fig. 8

Fig. 8: A comparison of modelled and ERA-Interim Reanalysis mean energy period during the period 1999-2003 at points P1 and P2. Black dark line gives x=y line while black dotted lines gives 80% confidence interval. The red dotted line gives the linear fit.

Figure 9 shows monthly averaged (averaged over the period between 1999 and 2003) significant wave height and mean energy period at P1 and P2. Modelled and ERA-Interim Reanalysis monthly averaged significant wave heights at P1 are in very close agreement (RMSE = 0.09m), although they are in slightly less agreement at P2 (RMSE = 0.23m). However, the comparison of modelled and measured monthly averaged significant wave heights revealed (Fig. 5) that the model reproduced measured waves accurately, which reassures the ability of the model in correctly simulating significant wave heights. Modelled and ERA-Interim reanalysis monthly averaged mean energy periods at both P1 and P2 are also in good agreement, with RMSE at P1 of 0.7 s while that at P2 of 0.8 s.

The good agreement between the two wave models reassures the fact that the model used in this study is capable of capturing the wave climate in the west and south of Sri Lanka.

Location of Fig. 9

Fig. 9: A comparison of modelled (green) and ERA-Interim Reanalysis (yellow) monthly averaged significant wave height and mean energy period during the period 1999-2003 at points P1 (top) and P2 (bottom).

Considering the fact that the Northern Indian Ocean is one of the most climatologically complex and dynamic areas as a result of the seasonally reversing tropical monsoon system operating in this region (Anoop et al., 2015), the above comparisons revealed that the wave model is able to satisfactorily simulate the wave climate around Sri Lanka. The validated wave model was used to generate wave projections for the 25-year period between 1979 and 2003 at 6hr intervals.

4. Wave energy resource analysis and characterisation

Twenty-five-year wave simulations from 1979 to 2003, that represent the prevailing wave climate in the Sri Lanka region, is used in this study to investigate wave power resource. To examine the available wave power around Sri Lanka at a broad scale, the spatial distribution of available average wave power around the island was computed using the 25 years wave data (Fig. 10). Wave power (*P*) was determined from Equation (2), using the mean energy period (T_{m-10}) given in Equation (1) to accommodate the randomness of the wave climate (MARINET, 2015). Wave data from all grid points of the Sri Lanka regional wave model grid points are used in this calculation.

$$P = 0.49 H_s^2 T_{m-10} \tag{2}$$

where *H*s ($= H_{mo} = 4\sqrt{m_0}$) is significant wave height of individual waves.

Location for Fig. 10.

Fig. 10: A spatial map of time averaged wave power distribution (averaged over the 25-year period between 1979 and 2003) for the entire coastline of Sri Lanka.

Figure 10 reveals that a substantial amount of wave power is available around the coast from the south-west to south-east of Sri Lanka. The average wave power available in this region is comparable to some of the highest wave power resource available world-wide (e.g. Neill et al., 2017; Hughes and Heap, 2010). The north-west to the east coastline contains considerably less amount of wave power, mainly as a result of limited fetch and sheltering from the mainland India. Therefore, proceeding analyses will be focused on the south-west to south-east coast of Sri Lanka. The figure also reveals that the available wave power resource significantly varies from the offshore to nearshore.

Although a substantial wave power resource is available in the southern Sri Lanka, a seasonal variation of wave power is expected due to the tropical south-west monsoon, which may impact the stability of the resource over time. This is examined by calculating the monthly-averaged wave power (Fig. 11). Wave simulations of all twenty five years from 1979 to 2003 were used for monthly averaging. The results reveal that the monthly-averaged wave power in the south-west to south-east of Sri Lanka lies between 7-15 kW/m except during the monsoon season between May and September, where it reaches 25-30 kW/m.

Location of Fig. 11

Fig. 11 Spatial distribution of monthly-averaged wave power (averaged over the modelled 25-year period between 1979-2003) for the entire coastline of Sri Lanka.

Although the average wave power and its seasonal variation is broadly uniform along the south-west to the south-east coast of Sri Lanka, spatial variabilities of the width and depths of the narrow continental shelf, direction of wave approach relative to the coast and the nearshore wave transformation processes taking place as a result of local variations of the seabed on the shelf may induce localised spatial variabilities to the wave climate and hence the wave power. Eighteen locations around the coast from the south-west to south-east coast, which include nine offshore and nine corresponding nearshore locations, were selected for a detailed analysis of spatio-temporal variability of wave power in this region (Fig. 12). The selected nearshore points are located between the 20m and 30m water depths and at distances less than 2.5km from the shoreline while offshore points are located between 60m and 100m water depths and at distances between 7-25km from the shoreline. All offshore points are located on the continental shelf.

Location of Fig. 12

Fig. 12 - Eighteen nearshore (PN-1 to PN-9) and offshore (PO-1 to PO-9) locations selected along the south-west to south-east coast of Sri Lanka for detailed wave resource analysis.

In Figure 13, wave power at the selected offshore (Fig. 13(a)) and nearshore (Fig. 13(b)) locations are shown. A considerable longshore variation of wave power can be seen from the south-west to the south-east. The highest offshore wave power is available in the south-west and south at locations from PO-3 to PO-7. A significant proportion of wave power at these points falls within the 20-30 kW/m band. On the other hand, most power at points PO-8 and PO-9 is between 10-20 kW/m while that at PO-1 and PO-2 is between 5-15 kW/m. The dominant direction at all offshore points is mostly south and south-west, however, a small amount of power is available from the waves reaching from the south-east at PO-8 and PO-9. Meanwhile, as can be seen in Figure 13 (b), the predominant wave approach direction at nearshore points PN-1 to PN-4 is south-west while that for PN-5 to PN-9 is south. Also, power at all nearshore points are smaller than that at their corresponding points.

Location of Fig. 13(a) and (b).

Fig. 13 (a) – Wave power distribution at the selected offshore locations (PO-1 to PO-9) around the south-west to south-east coastline of Sri Lanka.
Fig. 13 (b) – Wave power distribution at the selected nearshore locations (PN-1 to PN-9) around the south-west to south-east coastline of Sri Lanka.

Seasonal stability of locally available wave power is an important aspect in making decisions related to wave energy developments and device selection. Box-Whisker plots given in Figure 14 give monthly variability of wave power as well as the range of variability within a month. Top, middle and bottom black lines of the boxes give the third quartile, median and first quartile of wave power determined using the 25 year wave simulations between 1979 and 2003. The results reveal that during the south-west monsoon season, where larger wave power is available, the range of variability of wave power is also higher than the rest of the year at all locations. This can be attributed to the highly variable sea waves generated by the south-west monsoon winds. The range of variability of available offshore wave power differs along the coastline where the highest variability is found in the south-west and south of Sri Lanka (PO-1 to PO-7). Nearshore locations seem to follow a similar trend although the range of variability is significantly lower, understandably due to local transformation and dissipation processes that may occur in the nearshore as mentioned above.

Location of Fig. 14

Fig. 14- Box-Whisker plots of offshore and nearshore wave power around the south-west to south-east coastline of Sri Lanka. The plot was produced using the 25 years (1979-2004) projected wave data.

In addition to the seasonal monsoons, local climatic variabilities in the Indian Ocean such as the Indian Ocean Dipole (IOD) and Equatorial Indian Ocean Oscillation (EQUINOO) (Gadgil et al., 2004) may influence the regional wave climate and hence available wave power and power stability at inter-annual to decadal scale. To investigate wave power variability at timescales larger than the seasonal scale, annual average offshore and nearshore wave power at the selected offshore and nearshore locations were determined and evaluated in Fig. 15.

As seen in Figure 15, annual average wave power along the entire south-west to south-east coastline remains predominantly steady at inter-annual to decadal timescales although a faint cyclic variation where the average wave power drops slightly in every 5-7 years can be seen. However, this variability could not be directly correlated to any local climatic variability in the northern Indian Ocean. It can also be seen that the trend of temporal variability along the coast is fairly uniform. The figure also clearly reveals the change of annual average wave power from the offshore to the nearshore. At almost all points selected for our analysis, a significant reduction of annual average wave power can be seen in the nearshore, except at point PN-4 where both offshore and nearshore values differ only by 10-15%. In most other places, the reduction is in the order of 30%-50%. However, it should be noted that PN-4 and PO-4 points are relatively closer than others due to the very narrow continental shelf at that location.

Location of Fig. 15.

Fig. 15 – Annual average wave power along the south-west to south-east coast of Sri Lanka, calculated using projected wave climate for the period 1979-2003. Dark lines refer to the offshore points while broken lines refer to the corresponding nearshore points.

A summary of the available wave power and its stability around the south-west to south-east coast of Sri Lanka is given in Figure 16. In this figure, the radius of a circle is proportional to average wave power. The colour bar indicates the range of variability of power within the 25-year simulation period where red indicates high variability while green indicates low variability. Most available wave power is in the offshore of south-western and southern areas while relatively less energy is found towards the west and the south-east. As also seen in Figure 14, nearshore areas have a significantly low wave power. Power variability is high in the western and south western coasts of Sri Lanka (both nearshore and offshore) while the resource is more stable in the south, making the south of Sri Lanka as the most suitable area for wave energy harvesting.

Location of Fig. 16

Fig. 16 – A summary of spatial variation and range of variation of wave power around south-west to south-east coast of Sri Lanka. The radius of a circle is proportional to average

available wave power. Red, yellow and green in the colour bar indicates high, average and low range of variability of wave power.

4. Conclusions

Twenty-five years of simulated wave data that represent the prevailing wave climate are used in this study to investigate the spatio-temporal wave power resource around the island of Sri Lanka, located in the northern Indian Ocean. The high-resolution wave model used to generate wave projections is the last leg of a cascade of large-scale Indian Ocean (KU_IO) and medium scale India regional wave models developed using SWAN spectral wave model, which has been extensively validated using numerous wave data. The high-resolution Sri Lanka wave model outputs provided the opportunity to investigate the current wave energy resource around Sri Lanka in details, which provided essential scientific inputs for decision making and planning relating to site and device selection of future wave energy developments.

The results reveal that the seas surrounding the south-west to the south-east coasts of Sri Lanka have a substantial wave power resource (10-20 kW/m on average) all throughout the year, comparable to or exceeding wave power resource identified in many areas world-wide. The wave climate in this region is characterised by long distance swell waves approaching from the south and south-west directions thus making it suitable for energy harvesting. During the south-west monsoon season between the months of May and September, the local wave climate, and hence available wave power resource is strongly modulated by the monsoon-generated wind waves. As a result, wave power variability contains a strong seasonal signal where a higher than average wave power (20-30 kW/m on average) is available from May to September.

Although the entire south-west to south-east coast is found to have high wave power, some spatial variations can be seen. South-western region is found to have higher wave power than the southern and south-eastern regions. In addition, nearshore areas seem to have 20-50% less wave power than that at the corresponding offshore regions. Finally, wave power resource is predominantly stable at inter-annual to decadal scales although a weak cyclic signature can be seen. However, this signal, which has a period of 5-8 years, could not be correlated to any regional climatic variations operating in the equatorial Indian Ocean.

The actual power yield depends on the power matrix as well as the performance matrix of a particular wave energy device in response to wave directionality and the range of wave frequencies. The current study provides preliminary scientific evidence of the spatio-temporal characteristics of the available wave power resource to determine the desirable locations for wave energy harvesting around Sri Lanka and decide the most appropriate wave energy device that matches with the prevailing wave climate. Further studies comparing available and device specific power matrices is required to consolidate the selection of a specific device.

Acknowledgement

The authors acknowledge the financial support provided by Swansea University through the Global Challenge Research Fund project 'Wave energy resource characterisation for Sri Lanka in a changing ocean climate'. Dr. Nalin Wickramanayake of the Open University of Sri Lanka and Mr Sueewa Ranawaka of the Coast Conservation and Coastal Resource Management in Sri Lanka are greatly acknowledged for sharing available information and very insightful discussions held during the preparation of this manuscript. Bahareh Kanranzad acknowledges Japan Meteorological Agency for providing the atmospheric model outputs to run the wave models. BK was supported by the Hakubi Center for Advanced Research at Kyoto University and JSPS Grants-in-Aid for Scientific Research—KAKENHI—supported by the Ministry of Education, Culture, Sports, Science, and Technology-Japan (MEXT).

References

Aboobacker, V. M., 2017, Wave energy resource assessment for eastern Bay of Bengal and Malacca Strait, Renewable Energy, 14 (A), 72-84.

Alonso, R., Jackson, M., Santoro, P., Fossati, M., Solari, S. and Teixeira, L., Wave and tidal energy resource assessment in Uruguayan shelf seas, Renewable Energy, 114, 18-31.

Amarasekera, H.W.K.M., Abeynayake, P.A.G.S., Fernando, M.A.R.M., Atputharajah, A., Uyanwaththa, D.M.A.R. and Gunawardena, S.D.G.S.P, 2014, A feasibility study on ocean wave power generation for the southern coast of Sri Lanka: Electrical feasibility, International Journal of Distributed Energy Resources and Smart Grids, 10(2), 79-93.

Anoop, T.R., Kumar, V.S., Shanas, P.R. and Johnson, G., 2015, Surface wave climatology and its variability in the North Indian Ocean based on ERA Interim Reanalysis, J. of Atmospheric and Oceanic Technology, 32, 1372-1384.

Bernhoff, H., Sjöstedt, E. and Leijon, M., 2006, Wave energy resources in sheltered sea areas: A case study of the Baltic Sea. Renewable Energy, 31(13),2164 – 2170.

Booji, N., et al., 1999. A third-generation wave model for coastal regions, part 1. Model description and validation. J. Geograph. Res. 104 (C4), 7649–7666.

Besio, G., Mentaschi, L., Mazzino, A., 2016, Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast, Energy, 94, 50-63.

Chamara R.N. and Vithana, H.P.V., 2018, Wave energy resource assessment for the southern coast of Sri Lanka, 6th International Symposium on Advances in Civil and Environmental Engineering, Kuala Lampur, Malaysia.

Coast Conservation Department (1997), Coastal Zone Management Plan, Sri Lanka.

Cornett, A.M., 2009. A global wave energy resource assessment. Sea Technol. 50, 59–64.

Folley, M. and Whittaker, T.J.T., 2009, Analysis of the nearshore wave resource, Renewable Energy, 34, 1709-1715.

Gadgil, S., Vinayachandran, P.N., Francis, P.A. and Gadgil, S., 2004, Extremes of the Indian summer monsoon rainfall, ENSO and Equatorial Indian Ocean Oscillation, Geophysical Research Letters, 31, L12213.

Gonçalves, M., Martinho, P. and Soares, C.G., 2014, Assessment of Wave energy in the Canary Islands, Renewable Energy, 68, 774-784.

Gunaratna, P.P., Ranasinghe, D.P.L. and Sugandika, T.A.N., 2011, Assessment of nearshore wave climate off the southern coast of Sri Lanka, Engineer, XXXXIV(02), 33-42.

Hasselmann, H. and Hasselmann, K., 1985, Computations and Parameterizations of the Nonlinear Energy Transfer in a Gravity-Wave Specturm. Part II: Parameterizations of the Nonlinear Energy Transfer for Application in Wave Models, J. Physical Oceanography, (15), 1378.

Hemer, M.A., Zieger, S., Durrant, T., O'Grady, J., Hoeke, R.K., McInnes, K.L. and Rosebroke, Uwe, 2017, A revised assessment of Austraila's national wave energy resource, Renewable Energy, 114, 85-107.

Hughes, M.G. and Heap, A.D, 2010, National scale wave energy resource assessment in Australia, Renewable Energy, 35, 1783-1791.

Iglesias, G., Lopez, M. Carballo, R. Castro, A. and Fraguela, J.A. 2009, Wave energy potential in Galicia (NW Spain), Renewable Energy, 34(11), 2323-2333.

Iglesias, G. and Carballo, R. 2010. Wave energy and nearshore hotspots: The case study of the SE Bay of Biscay, Renewable Energy, 35(11), 2490-2500.

Kamranzad B, Chegini V, Etemad-Shahidi A., 2016, Temporal-spatial variation of wave energy and nearshore hotspots in the Gulf of Oman based on locally generated wind waves, Renewable Energy, 94, 341-352.

Kamranzad, B., Etemad-Shahidi, A. and Chegini, V., 2013, Assessment of wave energy variation in the Persian Gulf, Ocean Engineering, 70, 72-80.

Kamranzad, B., Etemad-Shahidi, A. and Chegini, V., 2016, Sustainability of wave energy resource in southern Caspian Sea, Energy, 97, 549-559.

Kamranzad B, Mori N, 2019, Future wind and wave climate projections in the Indian Ocean based on a super-high-resolution MRI-AGCM3.2S model projection. Climate Dynamics. pp 1-20. https://doi.org/10.1007/s00382-019-04861-7.

Komen, G.J., Hasselmann, S. and Hasselmann, K., 1984, On the existence of a fully developed wind-sea spectrum, J. Phys. Oceanography, 14(8), 1271-1285.

Kopor, W., Ekkawatpanit, C. and Kositgittiwong, D., 2018., Assessment of ocean wave energy resource potential in Thailand, Ocean and Coastal Management, 160, 64-74.

Leijon, M., Bernhoff, H., Berg, M., Ågren, O., 2003. Economical considerations of renewable electric energy production-especially development of wave energy, Renewable Energy 8, 1201–1209.

Liang, B., Fan, F., Yin, Z., Shi, H. and Lee, D., 2013, Numerical modelling of the nearshore wave energy resources of Shandong Peninsular, China, Renewable Energy, 57, 330-338.

Liberti, L., Sannino, G., Carillo, A., 2013, Wave energy resource assessment in the Mediterranean, the Italian perspective, Renewable Energy, 50, 938-949.

Lin, Y., Dong, S., Wang, Z. and Soares, C.G., 2019, Wave energy assessment in the China adjacent seas on the basis of a20-year SWAN simulation with unstructured grids, Renewable Energy, 136, 275-295.

Luo, Y., Wang, D., Gamage, T.P., Zhou, F., Widanage, C.M. and Liu, T., 2018, Wind and wave dataset for Matara Sri Lanka, Earth Systems Science Data, 10, 131-138.

MARINET, 2015, A report on ‘Standards for wave data analysis, archival and presentation’.

Mirzaei, A., Tangang, F. and Juneng, L., 2014, Wave energy potential along the east coast of Peninsular Malaysia, Energy, 68, 722-734.

Mizuta R., Yoshimura H., Murakami H., Matsueda M., Endo H., Ose T., Kamiguchi K., Hosaka M., Sugi M., Yukimoto S., Kusunoki S., Kitoh A., 2012, Climate simulations using MRI-AGCM with 20-km grid. J Meteor Soc Jpn, 90A, 235–260.

Morim, J., Cartwright, N., Etemad-Shahidi, A., Strauss, D and Hemer, M., 2016, Wave energy resource assessment along the south-east coast of Austraila on the basis of a 31-year hindcast, Applied Energy, 184, 276-297.

Neill, N.P., Vogler, A., Goward-Brown, A.J., Baston, S., Gillibrand, P.A., Walkdon, S. and Woolf, D.K., 2017, The wave and tidal resource of Scotland, Renewable Energy, 114, 3-17.

Robertson, B., Hiles, C.E. and Buckham, B.J., 2014, Characterizing the near shore wave energy resource on the west coast of Vancouver Island, Canada, Renewable Energy, 71, 665-678.

Saket, A., Etemad-Shahidi, A., 2012, Wave energy potential along the northern coasts of the Gulf of Oman, Iran, Renewable Energy, 40 (1), 90-97.

Sannasiraj, S.A., Sundar, V., 2016. Assessment of wave energy potential and its harvesting approach along the Indian coast, Renewable Energy, 99, 398-409.

Schulz-Stellenfleth, J., Konig,T and Lehner, S., 2007, An empirical approach for the retrieval of integral ocean wave parameters from synthetic aperture radar data, Journal of Geophysical Research, VOL. 112, C03019.

Sheffer, H.J., Fernando, K.R.M.D and Fittschen, T., 1994, CCD-GTZ Directional wave climate study South-west coast of Sri Lanka, Report on the wave measurements off Galle.

Sierra, J.P., White, A., Mosso, C. and Mestres, M., Assessment of the intra-annual and inter-annual variability of the ocean wave resource in the Bay of Biscay (France), Energy, 141, 853-868.

SWAN Team, 2017, SWAN scientific and technical documentation, Delft University of Technology.

Thevasiyani, T. and Perera, K, 2014, Statistical analysis of extreme ocean waves in Galle, Sri Lanka, Weather and Climate Extremes, 5-6, 40-47.

Wijeratne, E.M.S and Pattiarachchi, C.B., 2017, Sea level variability in Sri Lanka waters, National Aquatic Resources, Agency, Sri Lanka.

Zheng, C.W., Li, C.Y., 2017. Propagation characteristic and intra-seasonal oscillation of the swell energy of the Indian Ocean, Applied Energy, 197, 342-353.

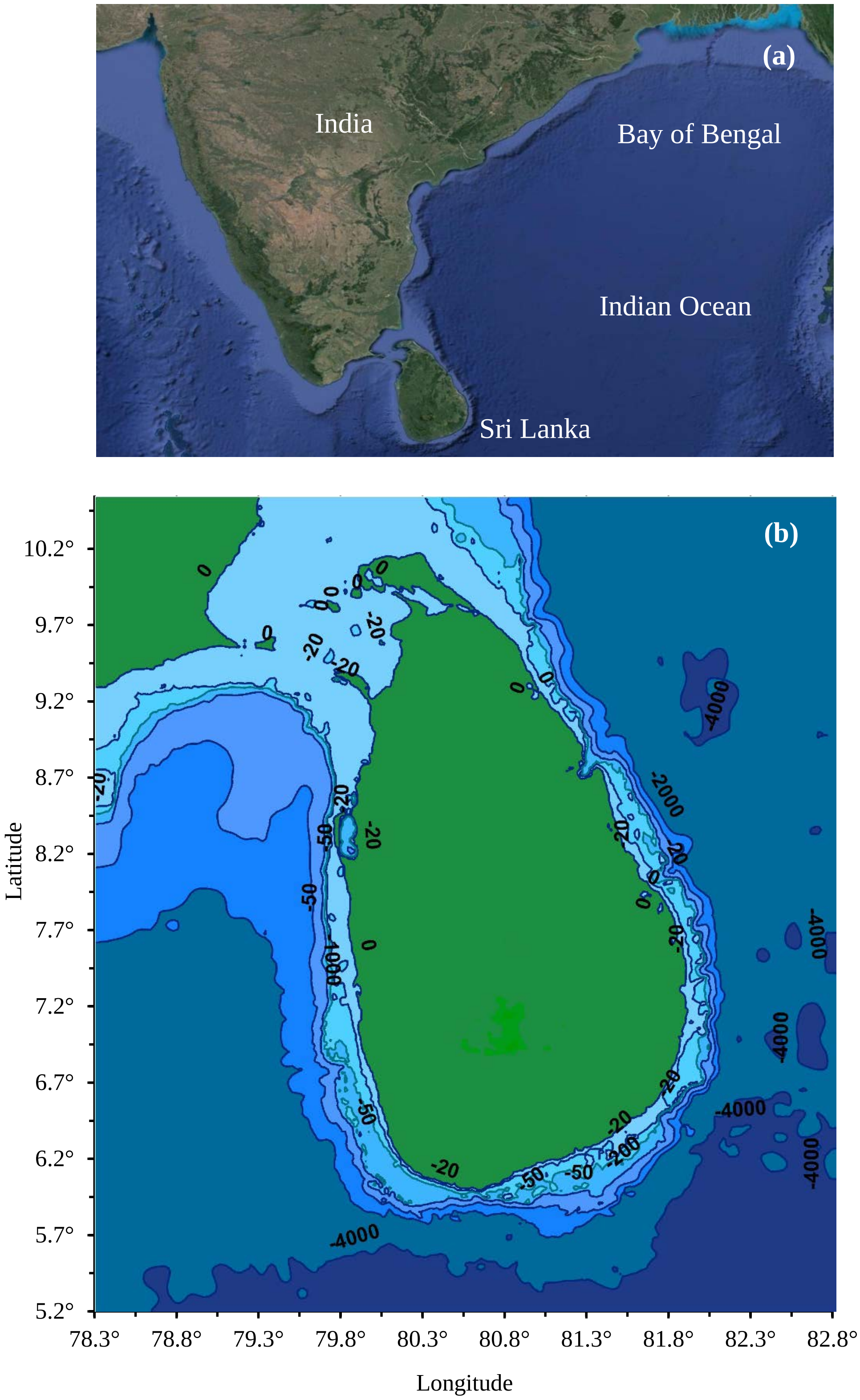


Fig. 1: (a) Map of Sri Lanka and its location in the Indian Ocean; (b) Sea bed contours around Sri Lanka showing the narrow continental shelf with a steep slope.

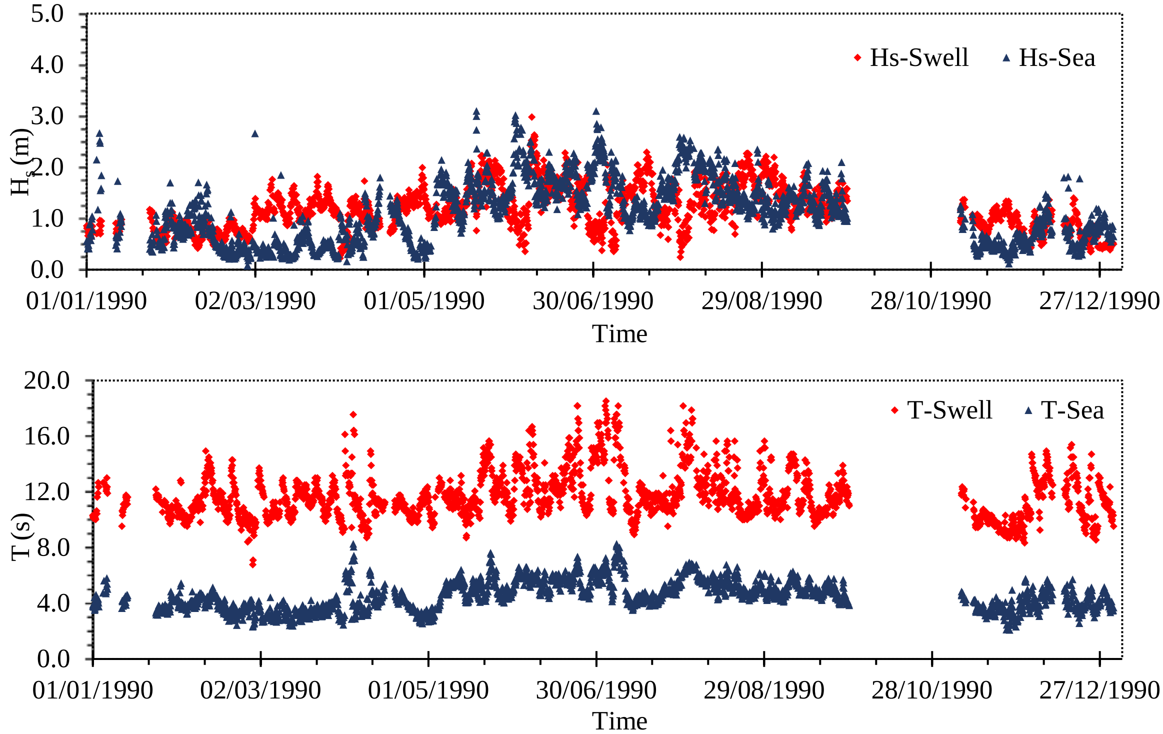


Figure 2a- A selection of measured sea/swell significant wave height (top) and period (bottom) time series offshore of Galle.

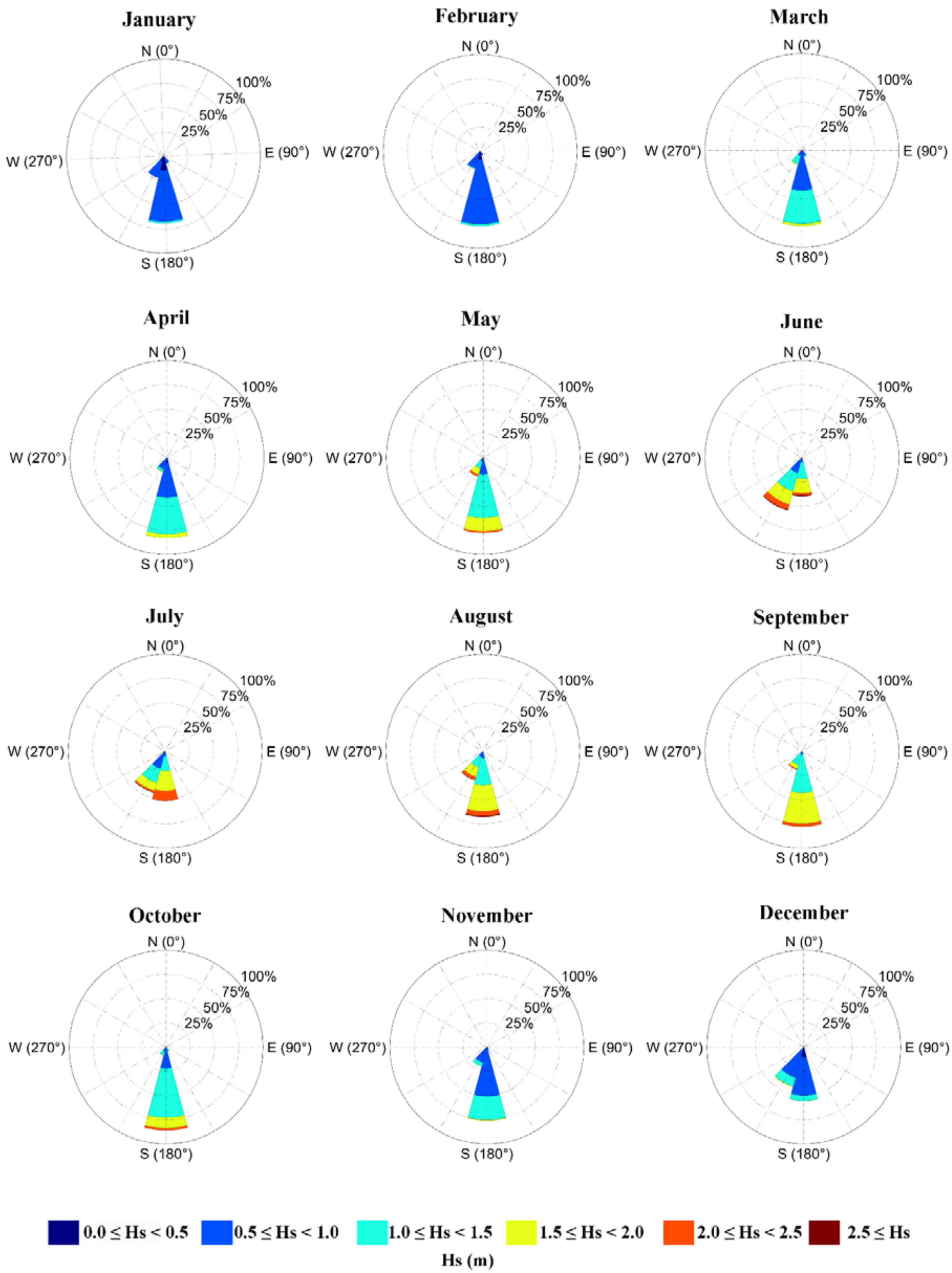


Figure 2b- Significant swell wave height roses determine from waves measured off the south-west coast of Sri Lanka in Galle over a period of 3 years between 1989 and 1992.

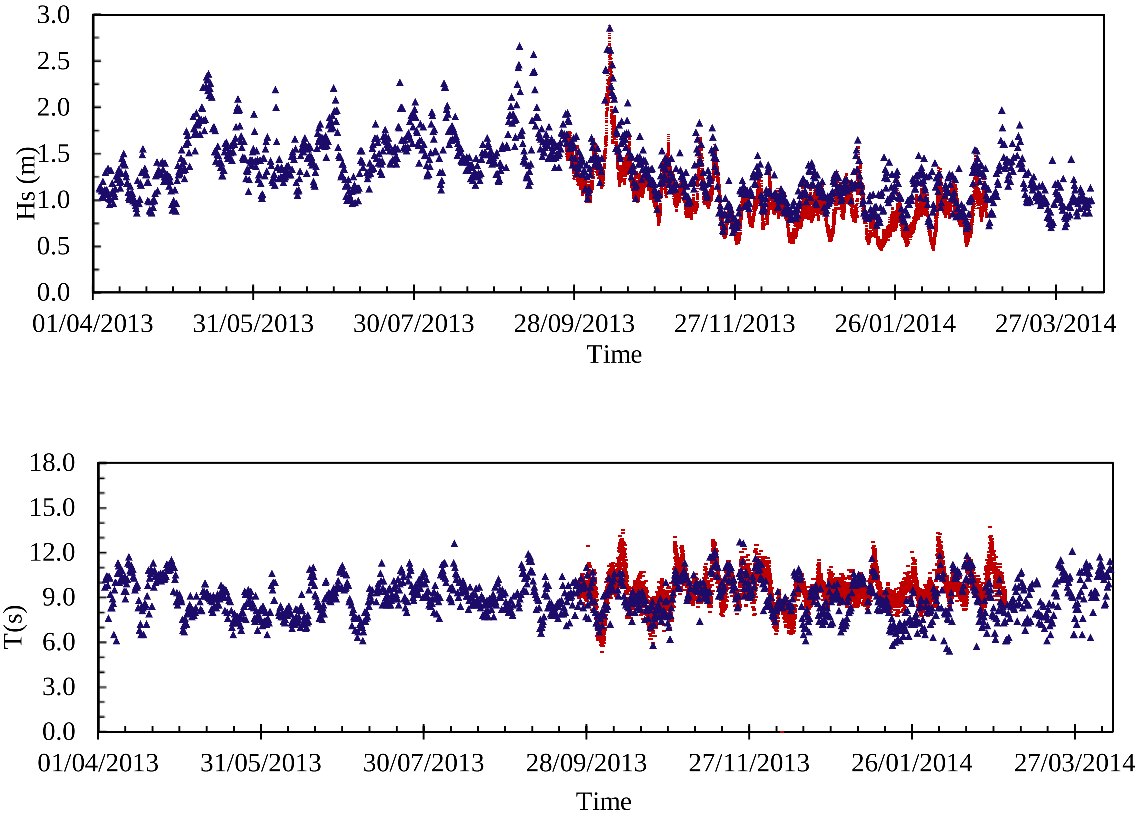


Figure 3a- Time series of measured significant wave height *H*s (top) and periods *T* (bottom) of Matara Buoy 1 (red) and Buoy 2 (blue).

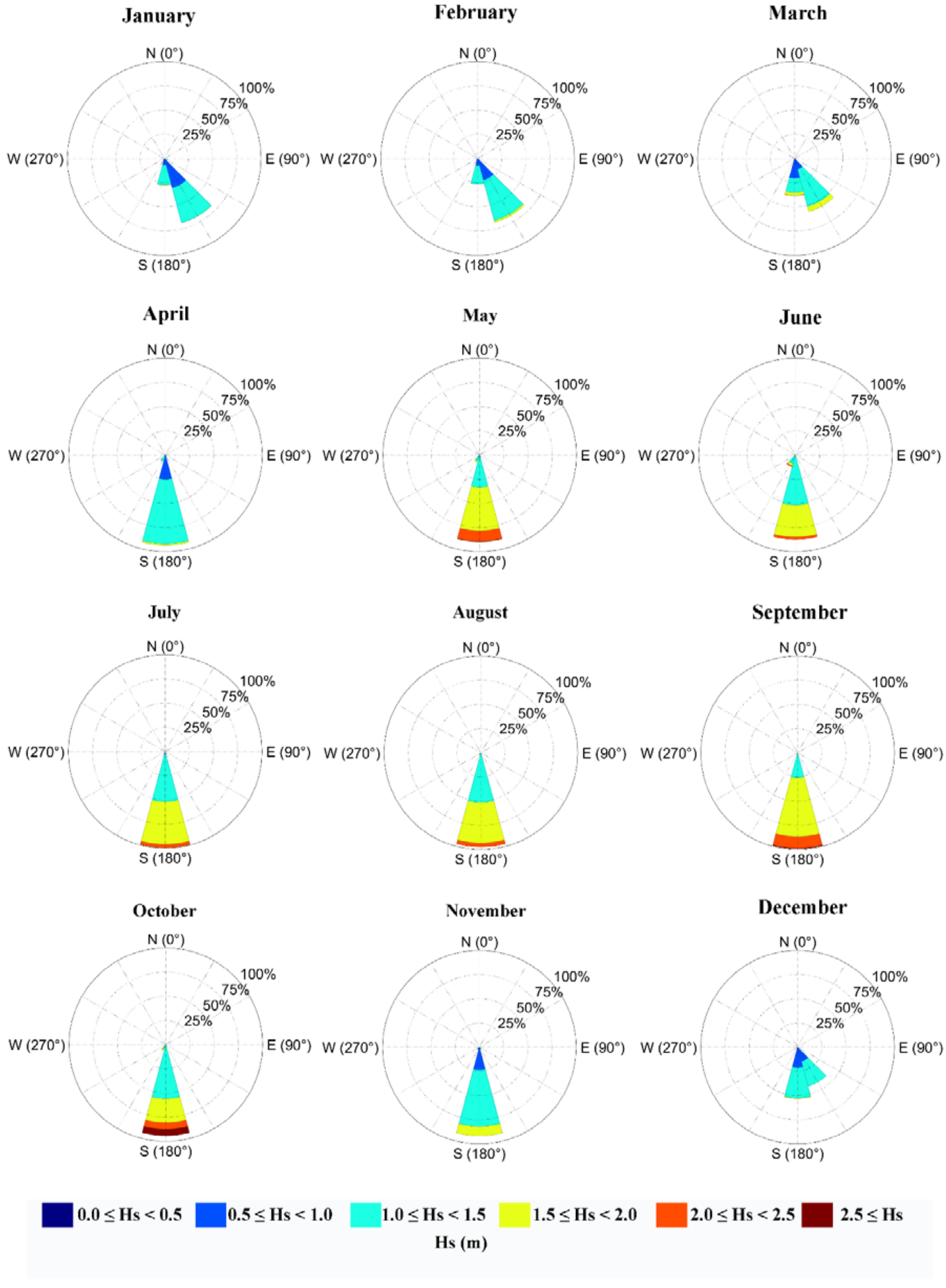


Figure 3b - Significant wave height roses determine from waves measured at Matara wave boy 2 during April 2013 – April 2014.

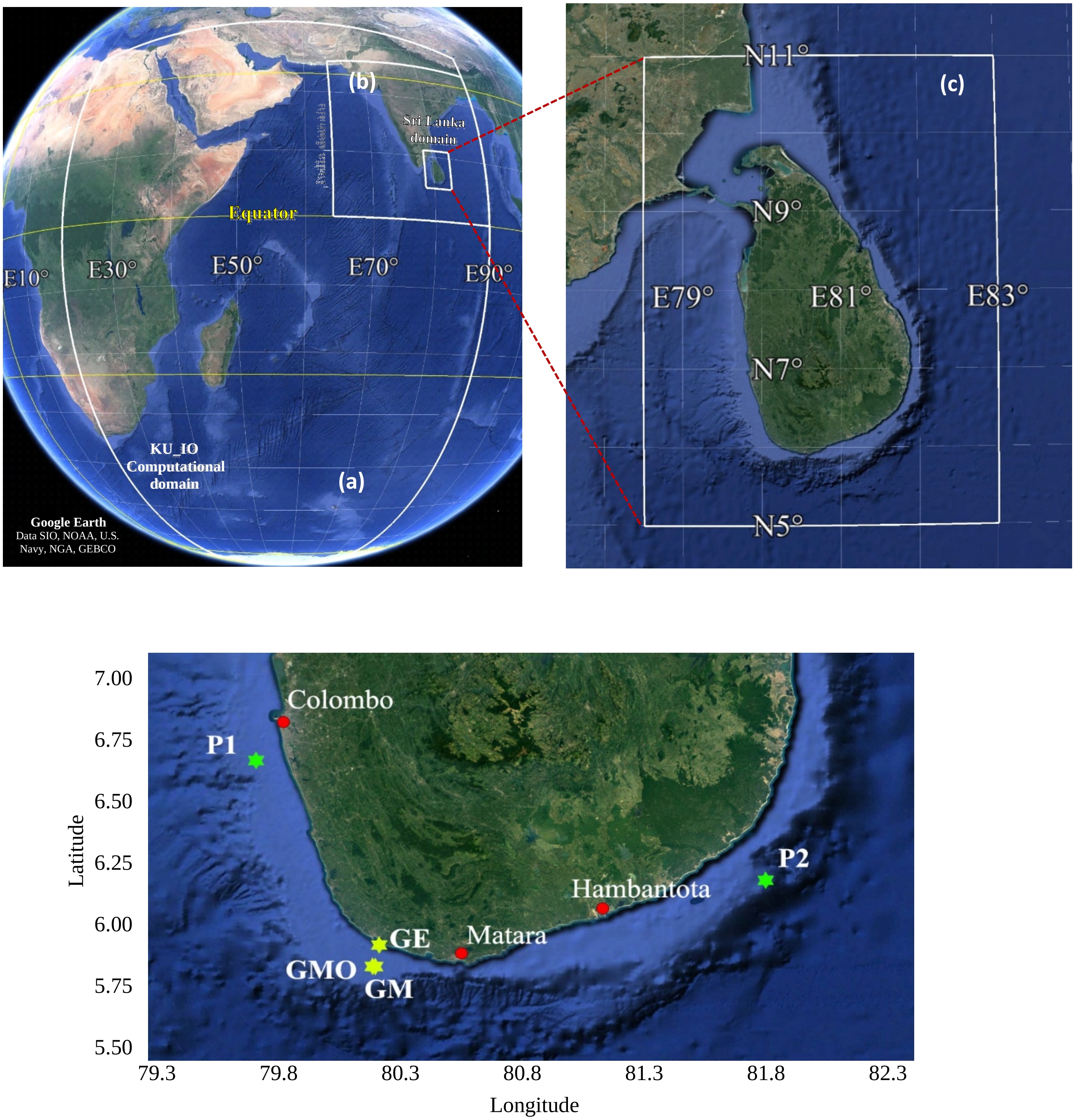


Figure 4- Indian Ocean (KU_IO) (a), India regional (b) and Sri Lanka regional (c) wave model domains (dark white lines) used for wave simulation for the Sri Lanka region [top]; and a map of southern Sri Lanka with measured/modelled/ERA Interim Reanalysis wave data locations used for wave model validation. GM - Galle (Measured), GE - Galle (ERA-Interim), GMO – Galle (Modelled). P1 and P2 are additional model validation points [bottom].

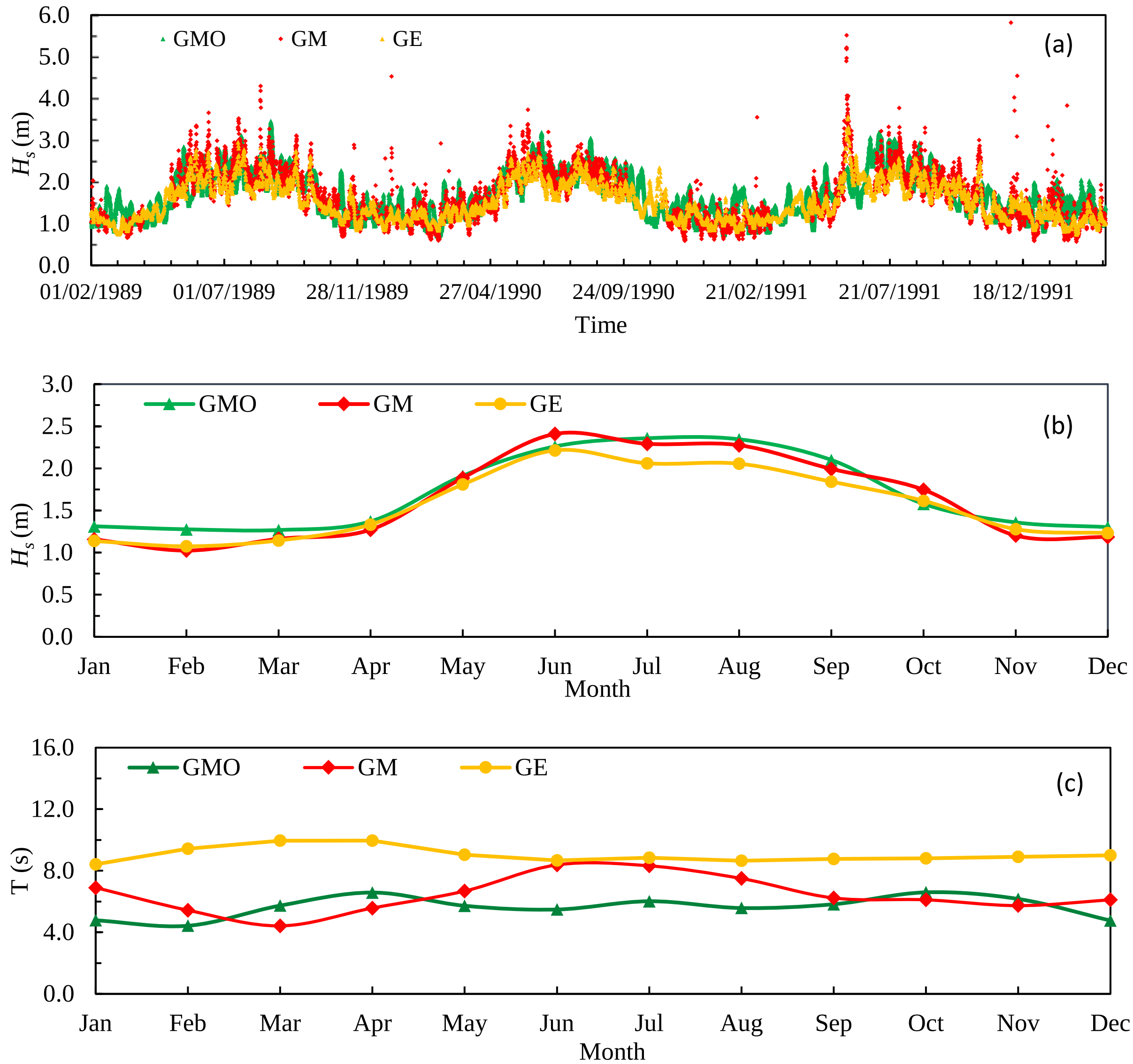


Fig. 5: Comparison of modelled [at GMO, (5.93° N 80.23° E)] (green), ERA-Interim Reanalysis [at GE (6.0N, 80.250E) (yellow) and measured [at GM (5.93 N, 80.23E)] (red) waves. (a) wave height time series; (b) Monthly averaged significant wave height; and (c) Monthly averaged wave period (T_{m02} for GM and GMO, mean period for GE). Monthly averaging is done taking the data for the period of 1989-1992.

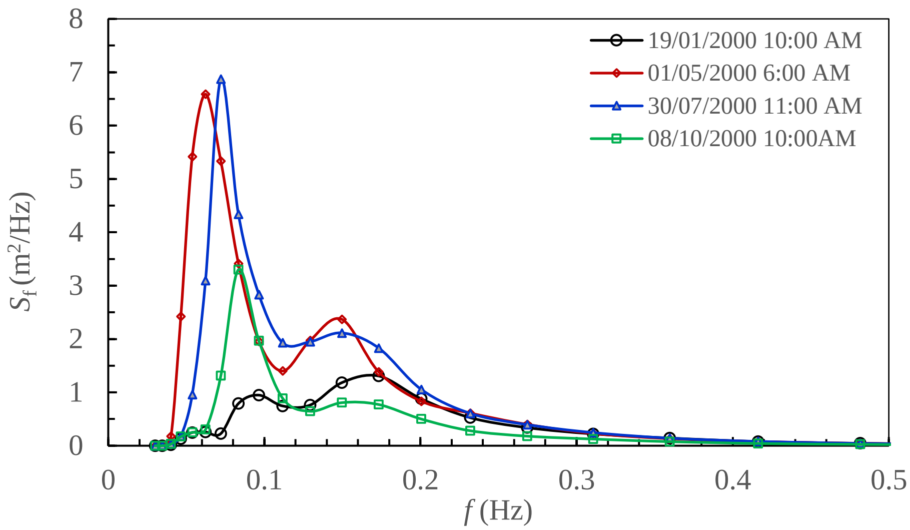


Figure 6 – A selection of modelled wave spectral densities S_f (m^2/Hz) against frequency *f* (Hz) in year 2000 at a model grid point (80°21'E, 5°54'N), located closest to the Galle wave buoy location.

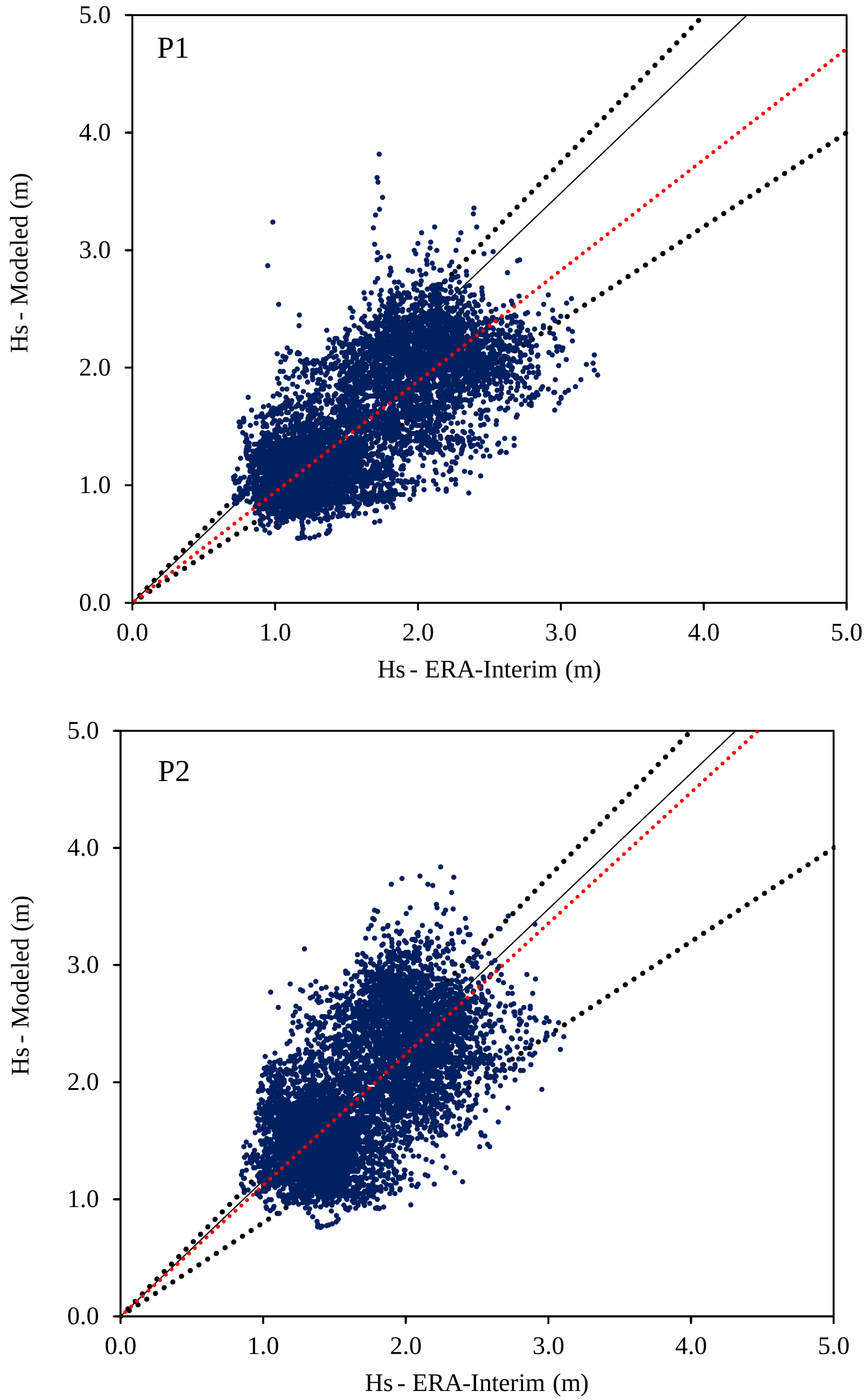


Figure 7- A comparison of modelled and ERA-Interim Reanalysis significant wave heights during the period 1999-2003 at points P1 and P2. Black dark line gives x = y line while black dotted lines gives 80% confidence interval. The red dotted line gives the linear fit.

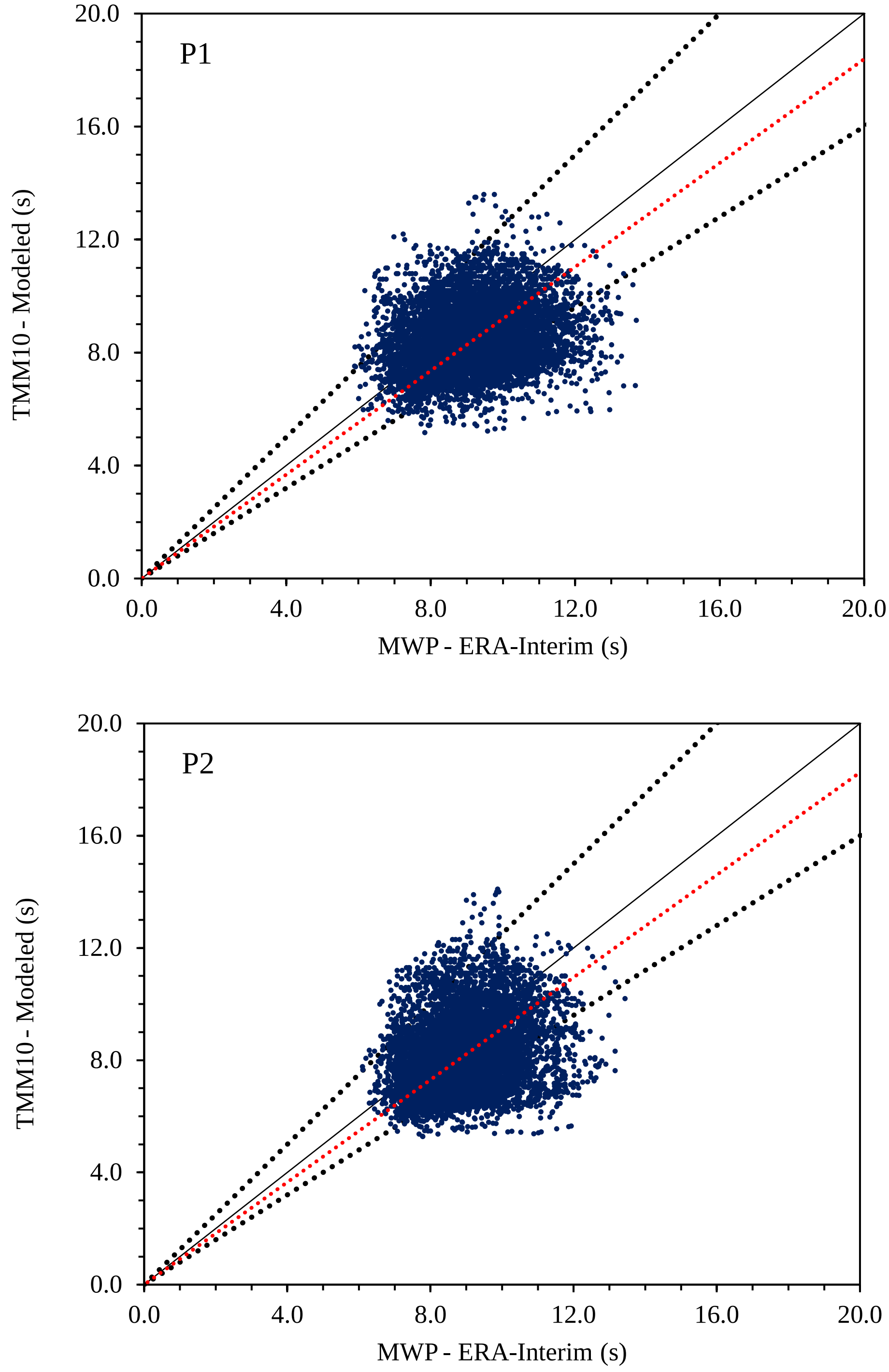


Figure 8 - A comparison of modelled and ERA-Interim Reanalysis mean energy period during the period 1999-2003 at points P1 and P2. Black dark line gives x = y line while black dotted lines gives 80% confidence interval. The red dotted line gives the linear fit.

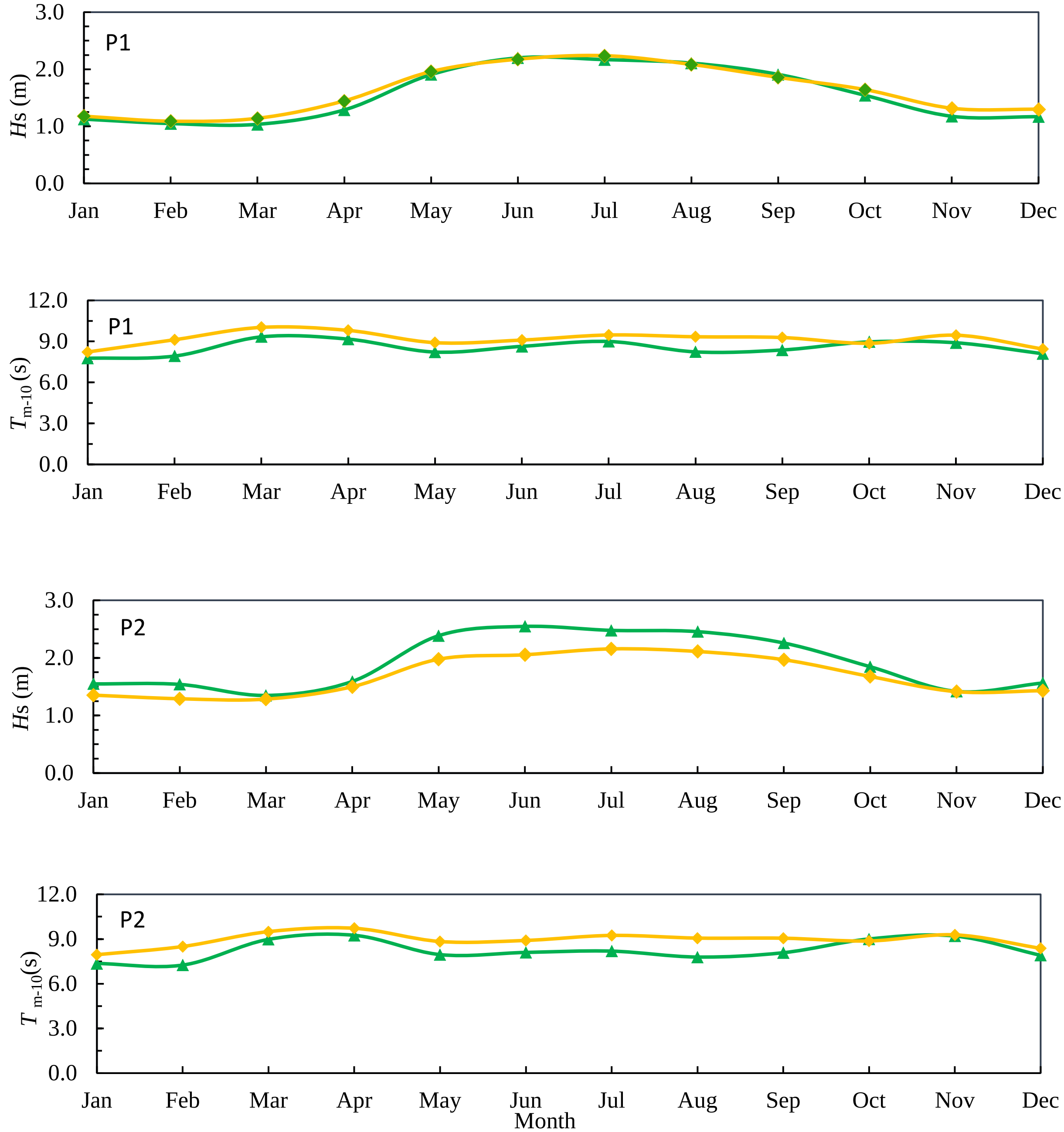


Figure 9- A comparison of modelled (green) and ERA-Interim Reanalysis (yellow) monthly averaged significant wave height and mean energy period during the period 2001 and 2005 at points P1 (top) and P2 (bottom).

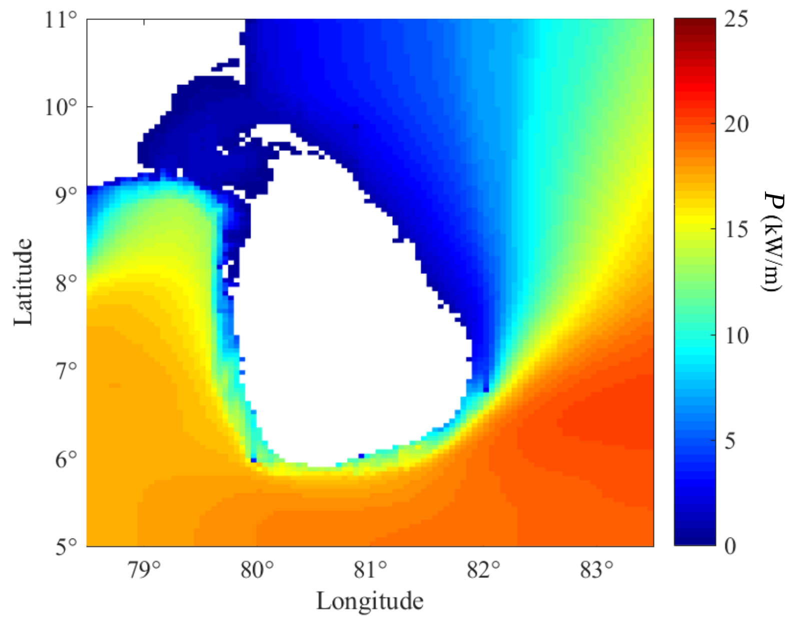


Figure 10 - A spatial map of average wave power distribution (averaged over the projected 25-year period between 1979 and 2003) for the entire coastline of Sri Lanka.

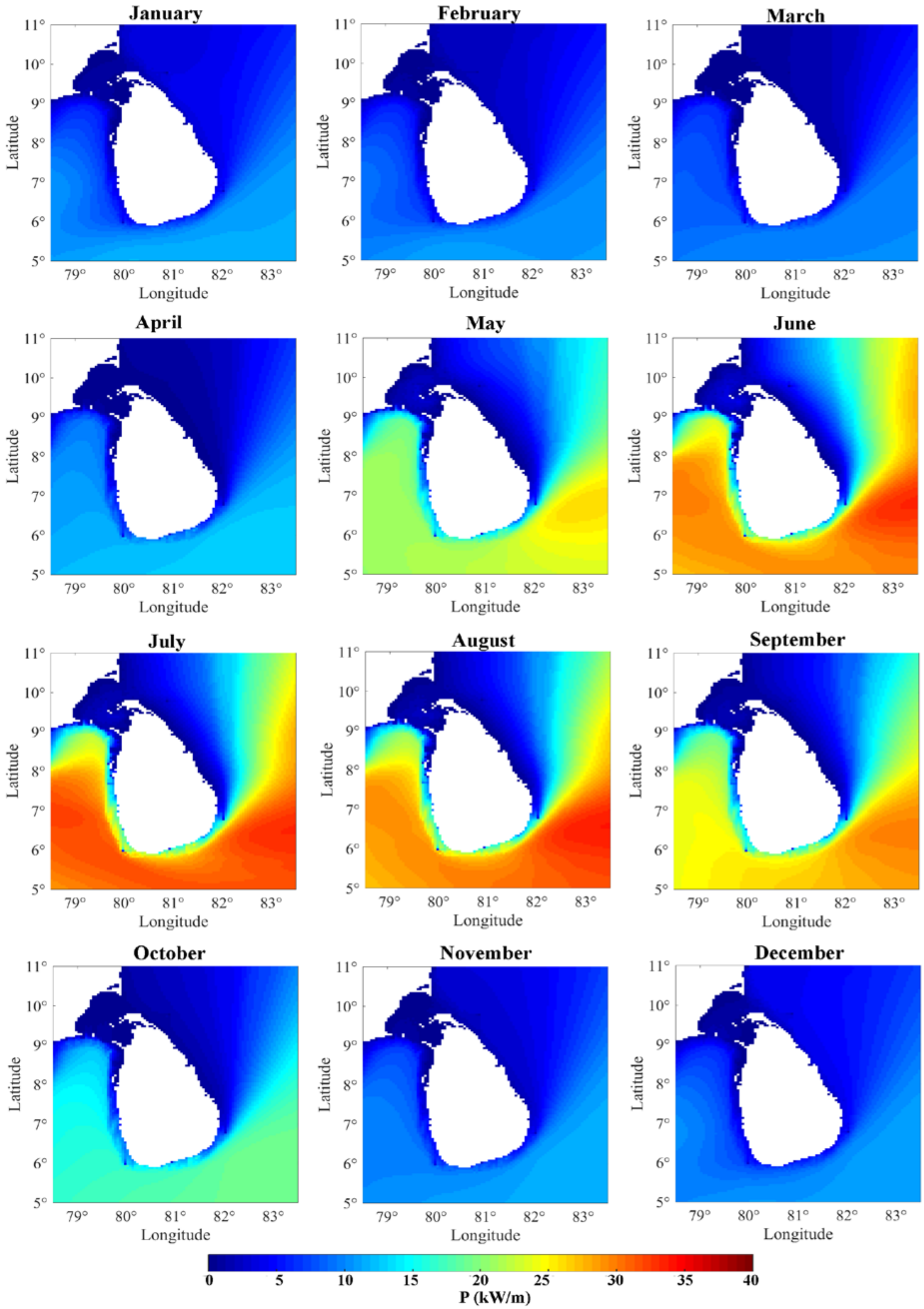


Figure 11- Spatial distribution of monthly average wave power (averaged over the modelled 25-year period between 1979-2003) for the entire coastline of Sri Lanka.

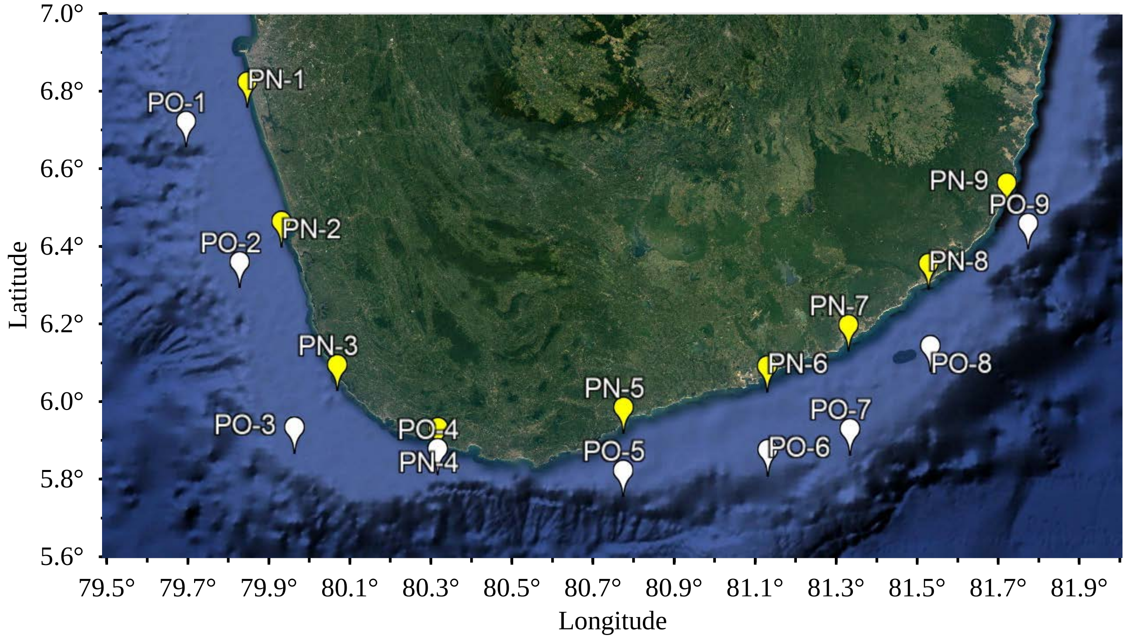


Figure 12 - Eighteen nearshore (PN-1 to PN-9) and offshore (PO-1 to PO-9) locations selected along the south-west to south-east coast of Sri Lanka for detailed wave resource analysis.

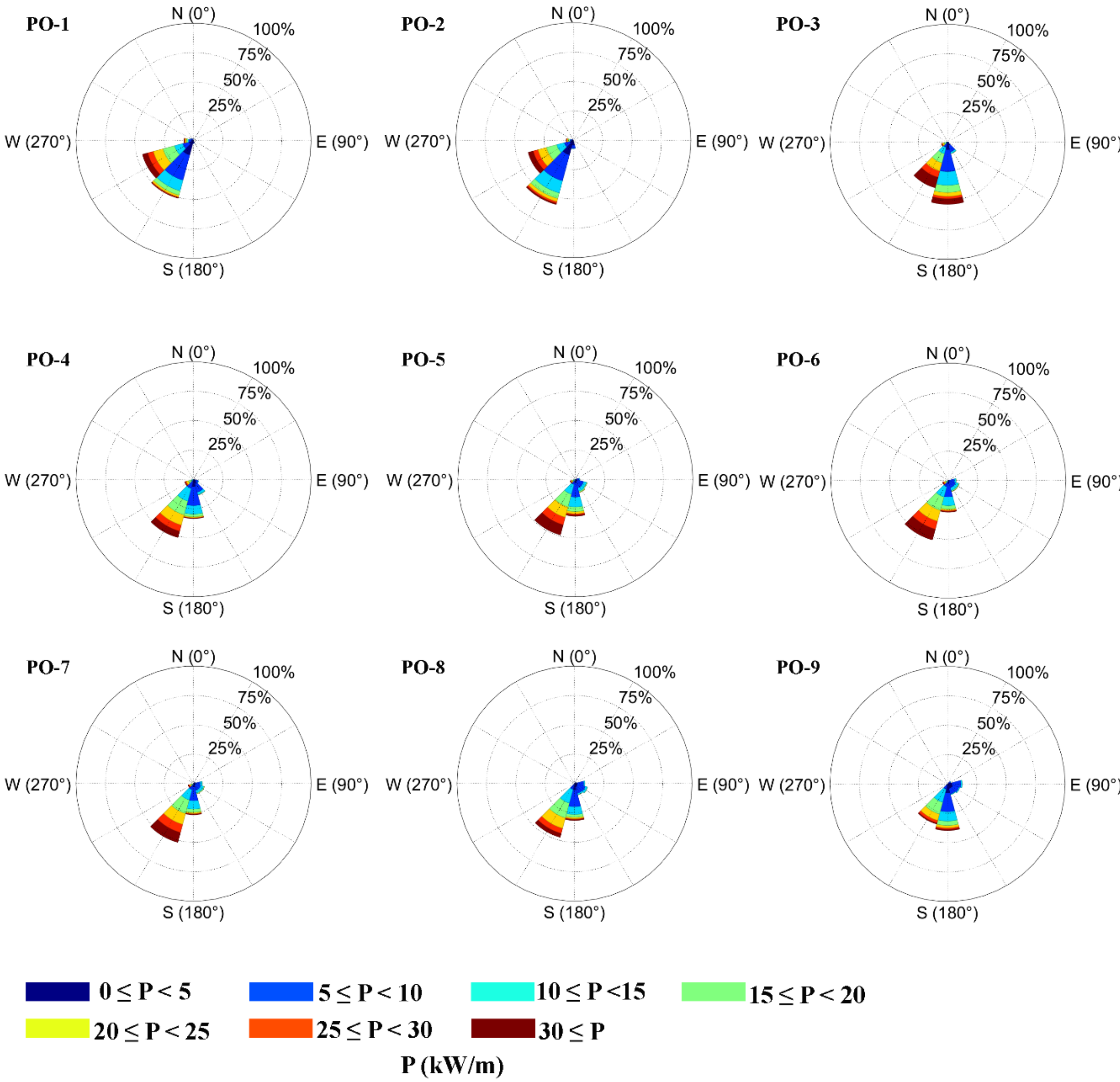


Figure 13 (a) – Wave power distribution at the selected offshore locations (PO-1 to PO-9) around the south-west to south-east coastline of Sri Lanka.

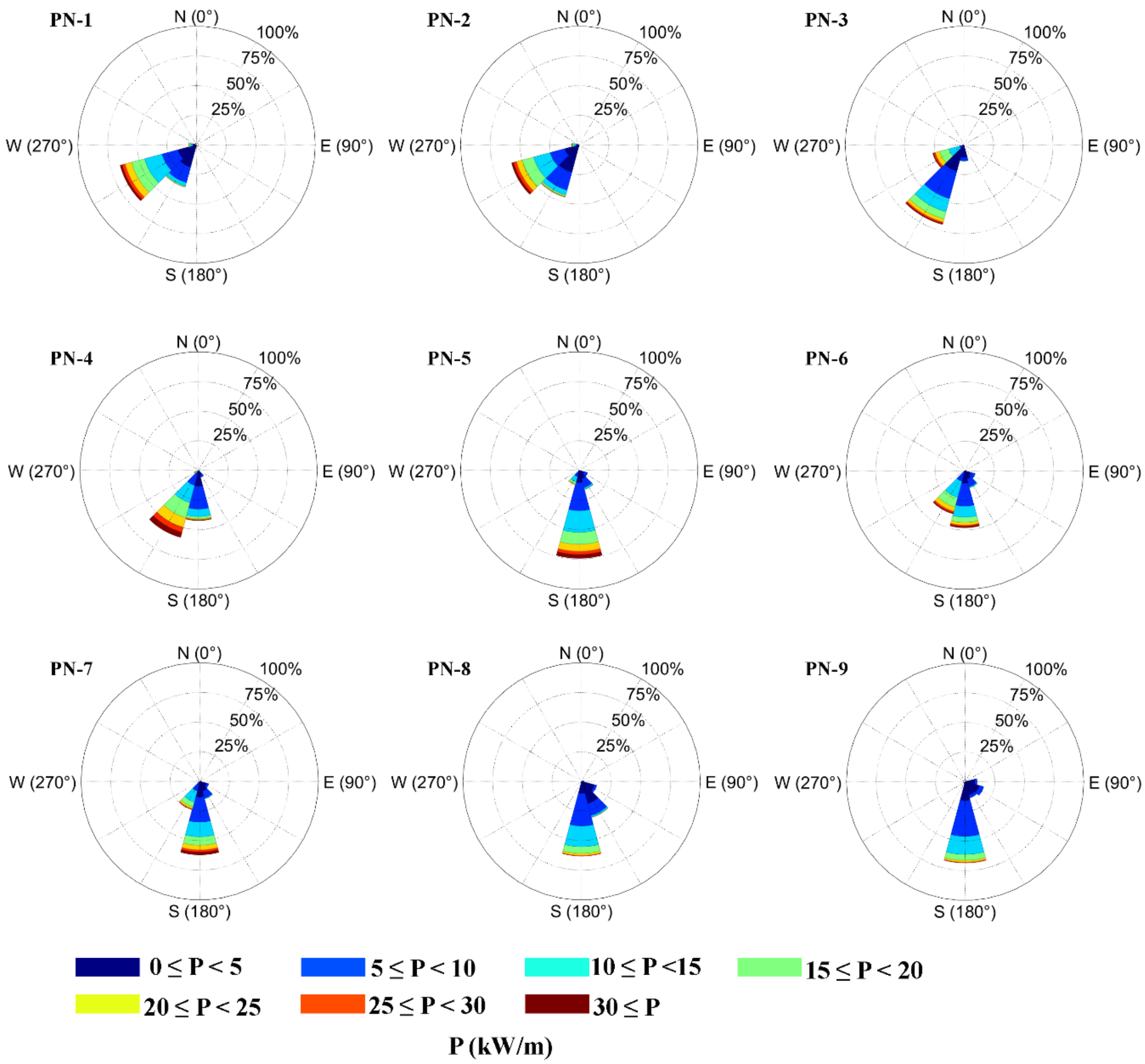
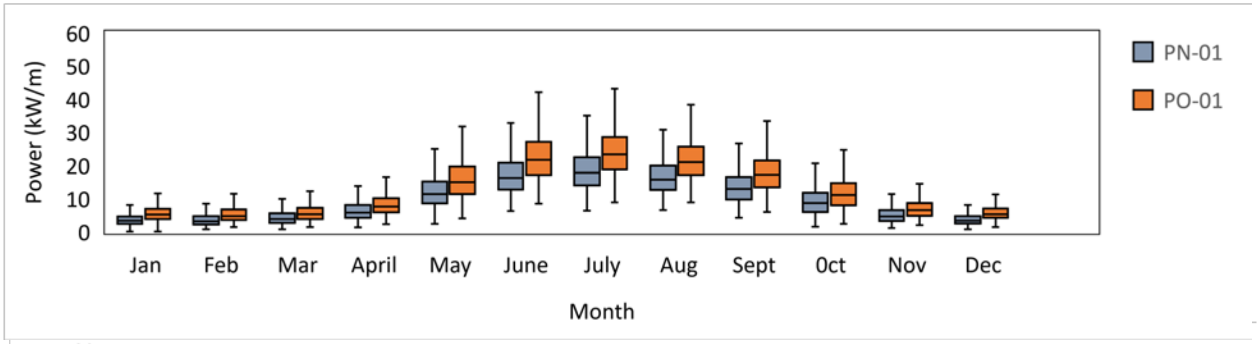
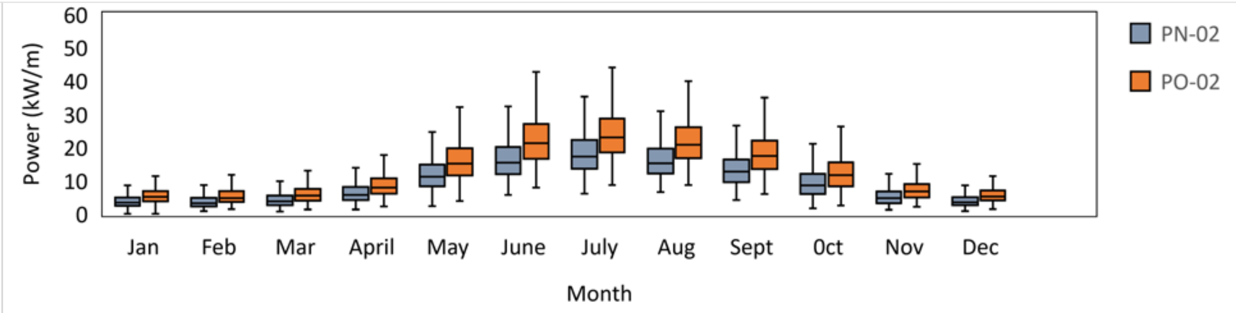
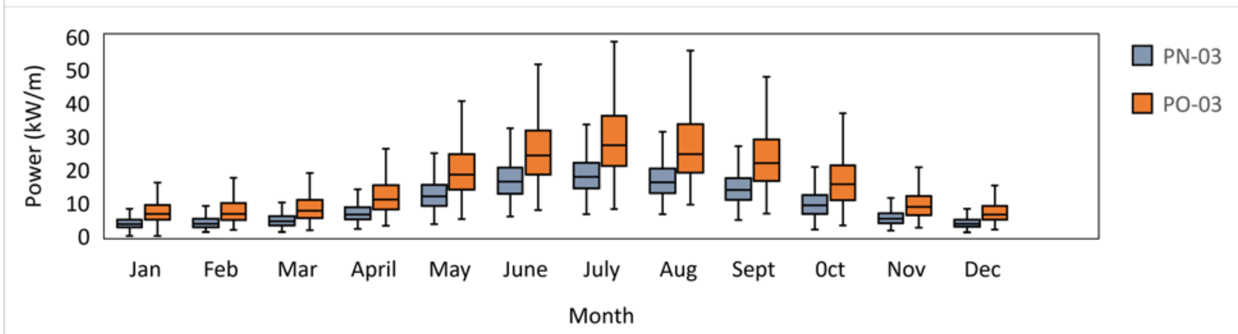
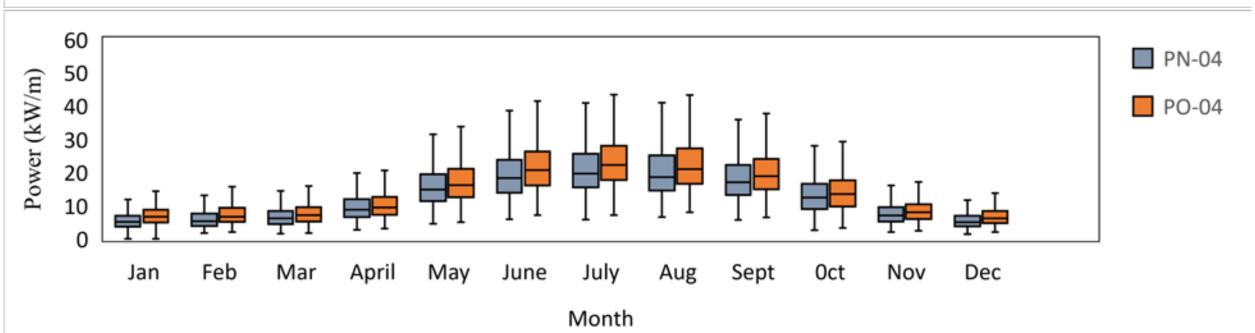


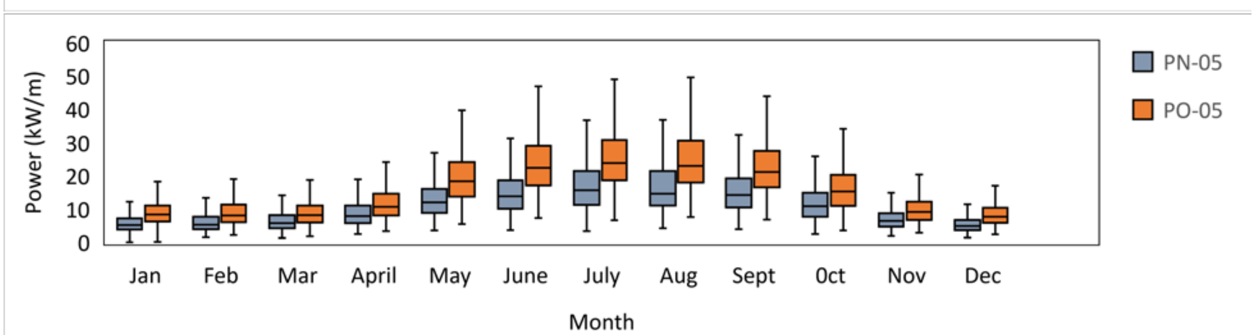
Figure 13 (b) – Wave power distribution at the selected nearshore locations (PN-1 to PN-9) around the south-west to south-east coastline of Sri Lanka.


Power (kW/m)
Month
PN-01
PO-01


Power (kW/m)
Month
PN-02
PO-02


Power (kW/m)
Month
PN-03
PO-03


Power (kW/m)
Month
PN-04
PO-04


Power (kW/m)
Month
PN-05
PO-05

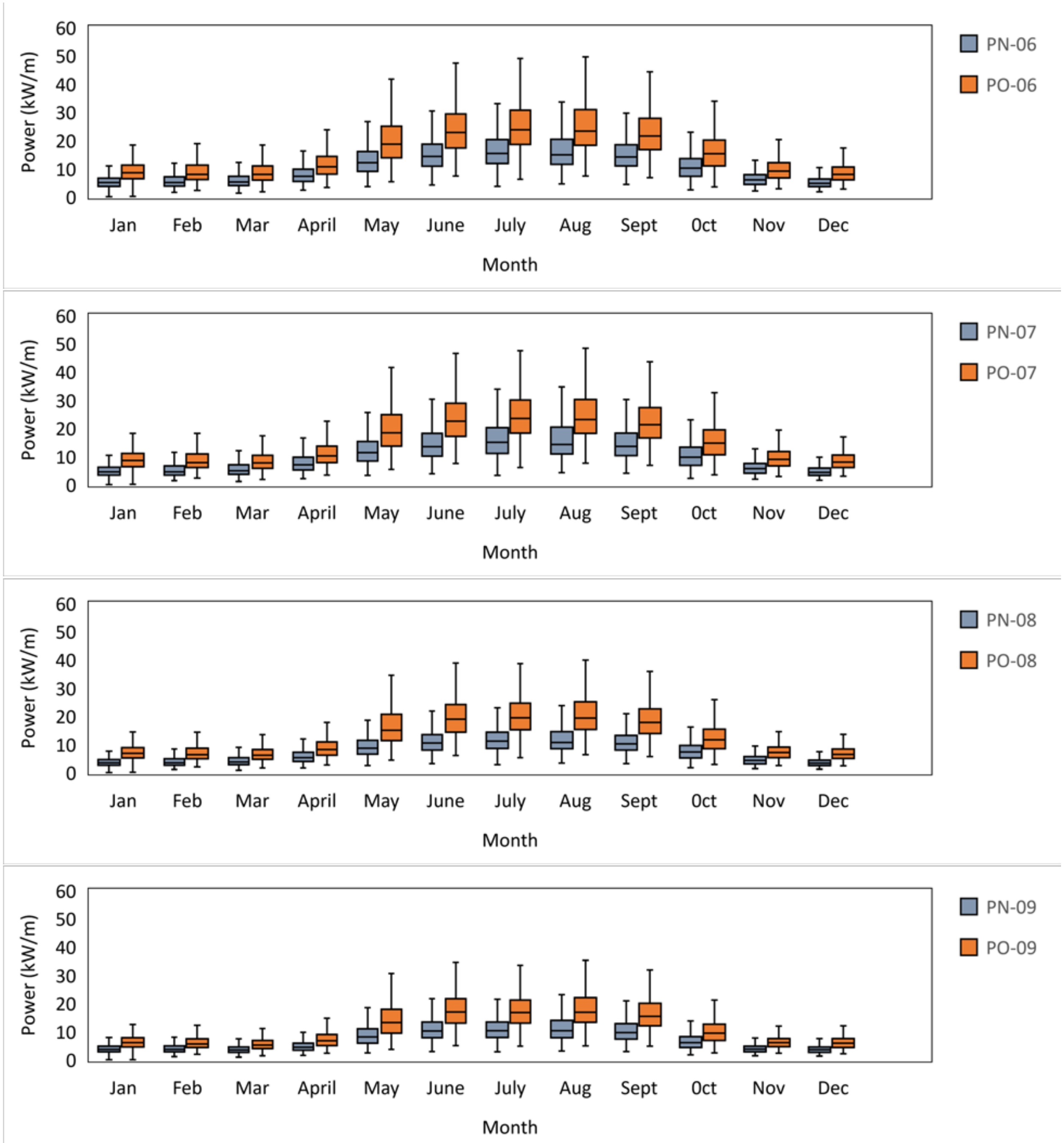


Figure 14 - Box-Whisker plots of offshore and nearshore wave power around the south-west to south-east coastline of Sri Lanka. The plot was produced using the 25 years (1979-2003) projected wave data.

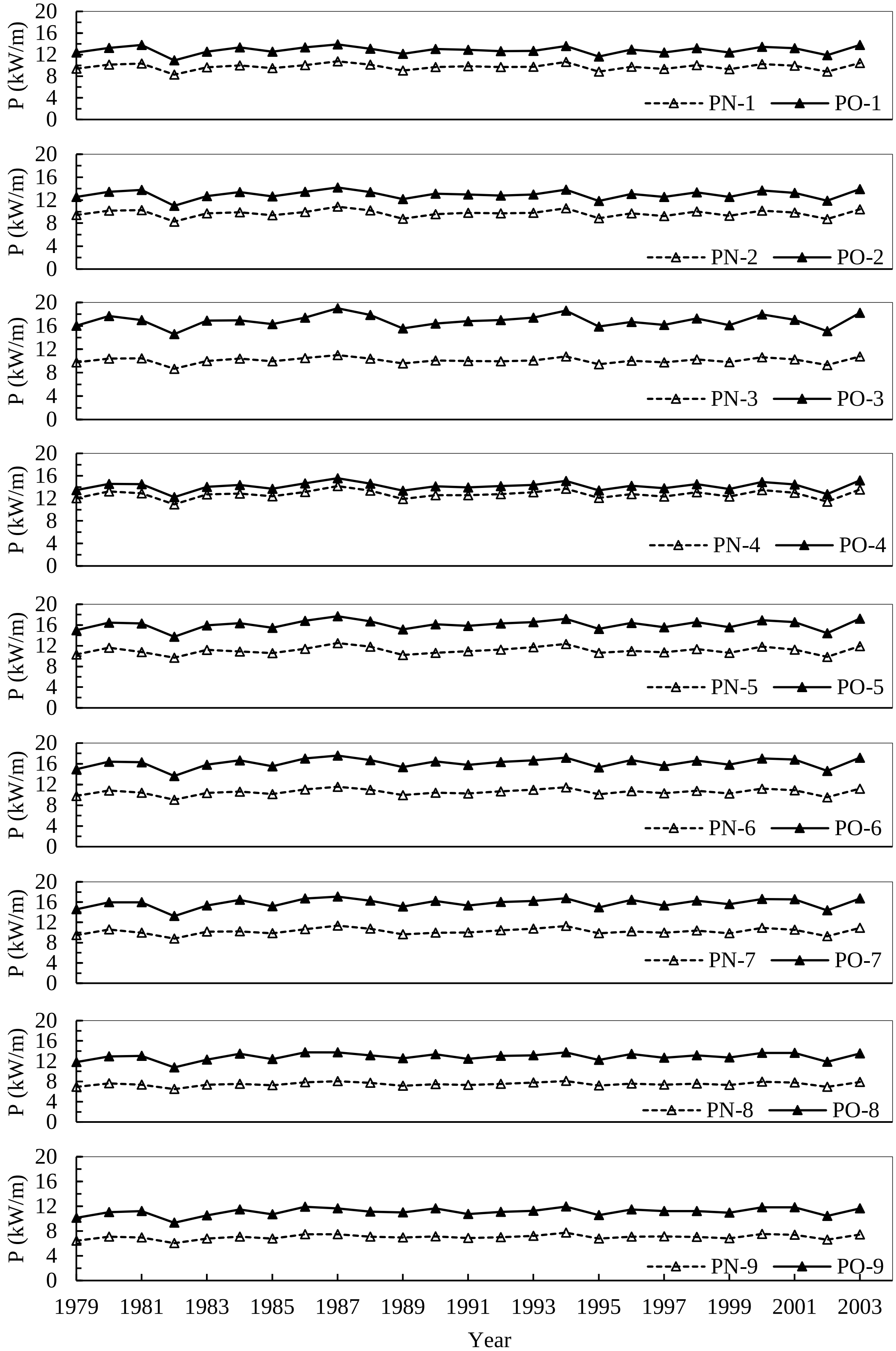


Figure 15 – Annual average wave power along the south-west to south-east coast of Sri Lanka, calculated using projected wave climate for the period 1979-2003. Dark lines refer to the offshore points while broken lines refer to the corresponding nearshore points.

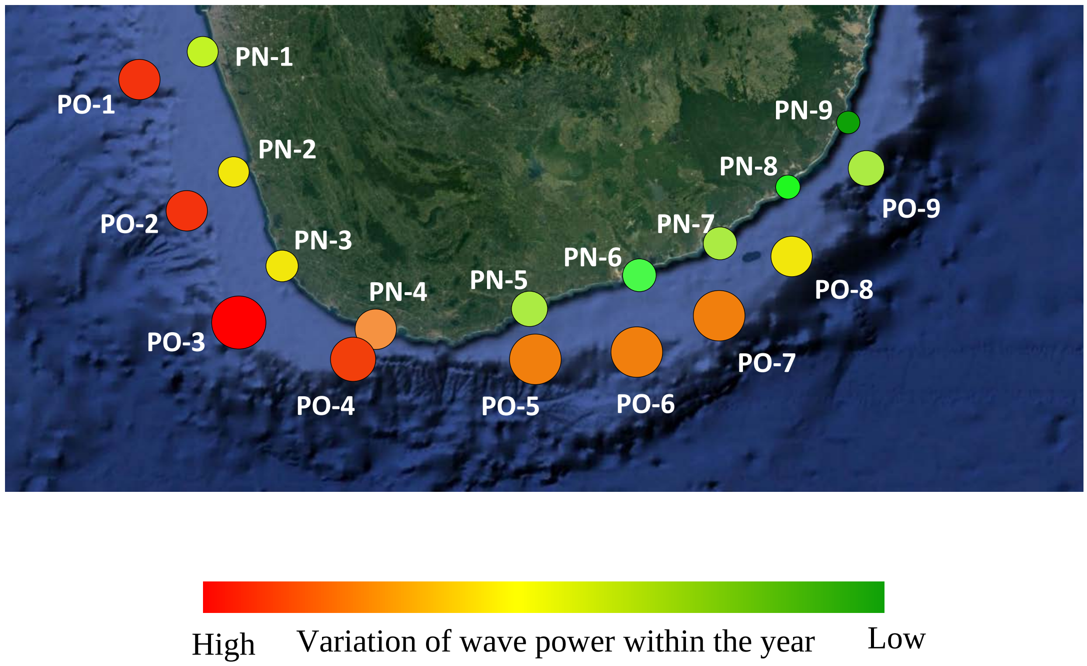


Figure 16 - A summary of spatial variation and range of variation of wave power around south-west to south-east coast of Sri Lanka. The radius of circles proportional to the amount of average wave power. Red, yellow and green in the colour bar indicates high, average and low range of variability of wave power.