

Article

Temporal Variations in Wave Systems in a Multimodal Sea State in the Coastal Waters of the Eastern Arabian Sea

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Abstract

Multimodal waves can significantly impact ocean–atmosphere interactions and affect coastal ecosystems. Due to the presence of waves created in different geographical areas, many wave systems coexist in coastal seas. Based on data collected with a directional waverider buoy, this study investigates fluctuations in multimodal sea states from March 2010 to May 2020 in the eastern Arabian Sea. The watershed-based spectral partitioning method is used to analyze 2D wave spectra obtained from measurements. Four-wave systems are present during pre- and post-monsoon periods, and three systems are detected during the monsoon (June–September). Interannual changes in significant wave height and peak wave period of different systems are investigated, revealing the maximum interannual variability of all wave systems in the inter-monsoon periods (May and October). The most energetic system during the pre-monsoon period is wind seas from the northwest direction, whereas during monsoon, swells from the southwest-west dominate. This pattern is similar across a spatial distance of 570 km along the western coastal waters of India. In the post-monsoon period, both systems (wind seas and swells) are present, with swells having slightly higher intensity.



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1. Introduction

Waves result from wind forces occurring at different temporal and spatial scales over the ocean [1,2]. Hence, multiple wave systems coexist at most open ocean locations, with varying intensities, frequencies, and directions [3]. Numerous studies have characterized the wave conditions at both regional and global scales, using data from in situ measurements, numerical simulations, and satellites [4–7]. The number and types of wave systems present in different oceans can vary based on factors such as wind patterns, available fetch, ocean currents, and geographical features [5]. For example, waves along the California coast consist of locally generated wind seas and swells generated in the North and South Pacific, and the wave spectrum can be separated by up to seven different partitions, each one with characteristic frequencies and directions [6]. In the eastern equatorial Pacific, Portilla et al. [8] identified four distinctive wave systems. In contrast, in the smaller ocean basins, the wave spectrum is unimodal since the region of wave generation is relatively small [9]. Multimodal waves influence both Stokes drift [10] and sediment transport along coastlines [11]. Waves with different frequencies and directions can transport sediments

differently along the coast and influence sediment transport along the coastline [11]. Swell waves exert significant influence on various air–sea interaction processes, thereby impacting weather and climate systems [12]. Identifying different wave systems present at a location is required when designing and deploying wave energy devices and marine structures [7]. Statistical analysis of satellite data [13] and reanalysis of wave hindcasts [14] indicated that waves generated offshore (swells) dominate 70% of the time in middle and higher latitudes and around 95% of the time in the tropics. The global distributions of the probability of swells and wind seas highlight the predominance of swells in the ocean, with notable seasonal variations identifying ‘swell pools’ at low latitudes and ‘seasonal swell pools’ at midlatitudes in the open oceans [15]. The global spectral wave climate in coarse resolution was presented by Echevarria et al. [16].

The most complete representation of ocean waves is given by the 2D wave spectrum (directional wave spectrum), which shows the wave spectral energy density distribution in frequency and direction. Wave systems present at a location can be recognized from 2D wave spectra using spectral partitioning techniques. The separation of 2D wave spectra was first proposed by Gerling [17] by using the lowest energy threshold to identify wave systems within the spectrum. Hasselmann et al. [18] utilized the watershed algorithm to separate wave systems present in the wave spectra, considering the wave spectrum as an inverted catchment area. Based on the watershed algorithm, several separation methods have been developed. The main difference between the methods lies in the identifying and handling of spurious partitions. Spurious partitions are detected using threshold parameters, such as low energy thresholds and square spectral distance [18–20]. Temporally averaged 2D wave spectra from the half-hourly data averaged over months represent all the sea states present at a location [19]. Although temporally averaged 2D wave spectra over one month cannot be used to determine environmental load conditions in designing structures, they are beneficial for planning operation and maintenance. For example, the direction of different wave systems must be considered when aligning a berthing facility. In the context of spectrum-based wave climate descriptions, the pioneering work of Portilla et al. [20] is likely the first to perform such an analysis. Subsequent research has shown that wave climate is closely linked to local or remote wind fields [15].

A comprehensive global overview of spectral wave climate by tracking partitioned wave climate systems, elucidating their propagation routes and transitions from wind seas to swells, has been identified at various sites in the past [6,15,16,20–23]. Zheng et al. [24] investigated the origin of multimodal waves based on spectral partitioning and wave system tracking in the North Indian Ocean (NIO). In the NIO, the wave systems are mainly caused by the southwest monsoon, northeast monsoon, southeast trade winds, and the southern storm belt [24]. Intense westerlies in the South Indian Ocean generate swells that propagate to the southern coast of Sri Lanka [25]. A study also indicated that the Sri Lankan land mass, located southeast of India blocks the long-period swells from the Southern Ocean from reaching the southeastern part of India [26]. Sreejith et al. [27] showed that sea ice concentration in the Southern Ocean is a critical factor in modifying wave characteristics in the NIO. Spectral changes in the NIO due to climate-induced changes are mainly characterized by a combination of the increases expected in Southern Ocean swells and the changes associated with tropical waves induced by trade winds [28,29]. The El Niño–Southern Oscillation (ENSO) the Indian Ocean Dipole, Boreal Summer Intra-Seasonal Oscillation, and the Southern Annular Mode cause significant changes in the wave climate over the Indian Ocean [30].

The wave climate in the Indian shelf seas of the NIO is inherently multimodal, shaped by complex and seasonally varying wind systems. These include reversing monsoon winds, sea breeze circulations, tropical cyclones, and remotely generated swells from

the southern Indian Ocean and even the Atlantic Ocean [31]. Wave regimes along the western shelf seas are significantly modulated by the Findlater Jet [32], the Oman low-level jet, Shamal winds [33], and Makran coastal winds [34], all of which contribute to the observed variability in swell systems. Shamal and Makran winds are prominent northerly wind systems influencing the northern Arabian Sea, particularly during the pre- and post-monsoon periods. Shamal winds, originating from the Middle East, often extend into the Arabian Sea and are capable of generating energetic swells (shamal swells) that impact the west coast of India. Makran winds evolve due to the modification of a northerly low-level jet by the Makran mountain ranges in southern Pakistan and typically propagate southward over the Arabian Sea, with wind speeds reaching up to 20 m/s near the source. This complex interplay of local and remote forcings underscores the need for robust spectral partitioning to isolate and analyze coexisting wave systems in the region.

Seasonal migration of the Intertropical Convergence Zone (ITCZ) southward during the boreal winter and northward in the boreal summer induces distinct seasonal reversals of winds over the Arabian Sea [35]. This dynamic governs the prevailing wind regimes that significantly modulate wave generation and directional spectra across the basin. During the southwest monsoon (June–September), southwesterly winds dominate the Arabian Sea, driven by differential heating between the landmass and the ocean. Mean wind speeds reach approximately 9.7 m/s, with peak values between 12.5 and 15.3 m/s [36]. These intense winds generate long-period, high-energy swells that propagate eastward, contributing to the dominant wave systems impacting the west coast of India and adjoining regions. In contrast, the northeast monsoon/post-monsoon period (October–January) brings relatively cooler, drier northeasterly winds due to high-pressure systems over continental Asia and low-pressure zones over the southern Indian Ocean. This reversal not only introduces a shift in wind direction but is also accompanied by the intrusion of north-westerly shamal winds originating from the Arabian Peninsula. The shamal winds, episodic yet influential, traverse the northern Arabian Sea and can induce moderate to steep wave events along the western Indian coast [37]. The pre-monsoon (February–May) period is characterized by weak and variable wind patterns, with mean wind speeds declining to approximately 5.6 m/s [36]. This period often witnesses transitional wind regimes that reflect sporadic gustiness, localized wind jets, and thermally induced flows. The resulting wave fields tend to be lower in energy, short-crested, and influenced more by local wind forcing than basin-scale swells.

Due to variations in the wind, the wave characteristics in the eastern Arabian Sea exhibit notable seasonal modulation, with an annual average significant wave height of around 1 m [38]. The southwest monsoon fosters large, long-period waves that contribute to sediment transport and coastal dynamics, while the northeast and pre-monsoon seasons present a more variable and regionally fragmented wave climate. These seasonal wind–wave couplings are crucial for understanding the directional wave energy distribution and for designing robust coastal and mooring systems in the region.

In the Arabian Sea, the multimodal waves are caused by seasonally reversing monsoon winds, trade winds, swells from the South Indian Ocean, and tropical cyclones [39]. The eastern Arabian Sea has multimodal wave environments containing southwest (SW) swells, Southern Ocean swells, and northwest (NW) swells apart from the wind seas [5,36–43]. In the coastal waters, the multimodal sea states are also formed due to the influence of sea breeze [44]. Nair and Kumar [45] analyzed the occurrences of double-peaked spectra in the eastern Arabian Sea. Previous studies on wind seas and swells in the Indian shelf seas have recognized swell dominance at maximum locations in the Arabian Sea [36,39] (and the references therein) and the dominance of wind seas and swells along the central west coast of India [45].

Previous studies along the eastern Arabian Sea have focused on understanding the two wave systems, i.e., wind seas and swells, based on partitioning of the 1D wave spectra, but have not considered other wave systems present in the study area [36–39]. Based on data obtained from the wave model, Amrutha and Kumar [40] identified four to seven types of distinct wave systems in the Indian shelf seas at deeper water depths. Reliable point observations have been obtained through wave buoys, which are the primary data source for 2D wave spectra. Partitioning 2D wave spectra allows for identifying the wave heights, periods, and directions of different wave systems.

Inspired by these facts, the current study attempts to identify wave systems of different meteorological origins in the coastal waters of the eastern Arabian Sea and their temporal and spatial variations over 570 km.

2. Materials and Methods

The datasets used in this study comprise the Datawell MKIII waverider buoys moored off Versova (10 m water depth), Ratnagiri (13 m water depth), Vengurla (15 m water depth), Karwar (15 m water depth), and Honnavar (9 m water depth) at locations along the eastern Arabian Sea (Figure 1).

For Ratnagiri, the dataset consists of 10 years of half-hourly records of wave spectra over the period from March 2010 to May 2020, while at other locations, data covering January–December 2017 were used. Spatially, Versova (northernmost location) and Ratnagiri are separated by ~230 km, Ratnagiri and Vengurla by ~130 km, Vengurla and Karwar by ~40 km, and Karwar and Honnavar (southernmost location) by 70 km. The buoys use vertical accelerometers mounted on a gravity-sensitive platform to measure heave. The output from the sensor is subjected to a low-pass filter with a cut-off frequency of 1.5 Hz and then sampled at 3.84 Hz. It is then subjected to a high-pass filter with a cut-off of 30 s and converted into a sample rate of 1.28 Hz [46]. Wave direction is based on the measurement of the horizontal motion of the buoy and correlating this motion with the vertical motion of the buoy. The direction represents the approaching angle of the waves, which increases clockwise, with 0° denoting true north. Two mutually perpendicular accelerometers are mounted on the buoys to measure the horizontal buoy motion. The wave fields, i.e., integrated wave parameters and the 2D wave spectra saved at half-hourly intervals, were used in this study. In order to examine the wave energy distribution over frequency and direction, monthly averaged wave spectra were estimated. For this study, only the months with data availability of at least 90% were selected.

The different wave systems present were identified by applying spectral partitioning of the measured 2D spectra using the partitioning algorithm of Douglas and Voulgaris [21], which is based on those of Hanson and Phillips [47] and Portilla et al. [8]. The 2D spectrum was first filtered using double convolution and then partitioned using the watershed algorithm. This approach inverts the spectral surface so that spectral peaks become catchments. The spectral partitioning method utilizes image processing algorithms to partition the wave spectrum into wave systems. The partition parameters calculated for each partition are the peak frequency, peak energy, and peak direction. For wind seas, a cut-off frequency (f_c) of 0.12 Hz was used, consistent with the 1D partitioning cut-off frequency [48]. The mutual peaks, i.e., adjacent peaks belonging to the same system, were merged if they satisfied any of the conditions given below [8,47].

For each partition, the significant wave height (H_s) was estimated from the spectral moments, and the peak wave period (T_p) was obtained from the wave spectrum.

1. If the spread of either peak (δf^2) satisfied the peak separation criterion $f^2 \leq k \delta f^2$, then the two peaks were combined. The value of the spread factor (k) was taken as 0.4.

2. If the squared distance between the two swell peaks was less than $(6 \times df)^2$, then the directional separation between the two peaks was less than 90° . Here 'df' is the difference between the frequencies of the two swell peaks.
3. Only the partitions above the noise level and those with peak frequencies below 0.58 Hz were selected.
4. The remaining partitions that did not have a valley between them were merged.

The wave buoys were deployed at relatively shallow waters (9–15 m), where wave refraction can significantly alter wave directions. This refraction effect may cause changes in the 2D spectra. Since the spectral partitioning algorithm relies on directional separation to identify distinct wave systems, such changes could potentially affect the partitioning results.

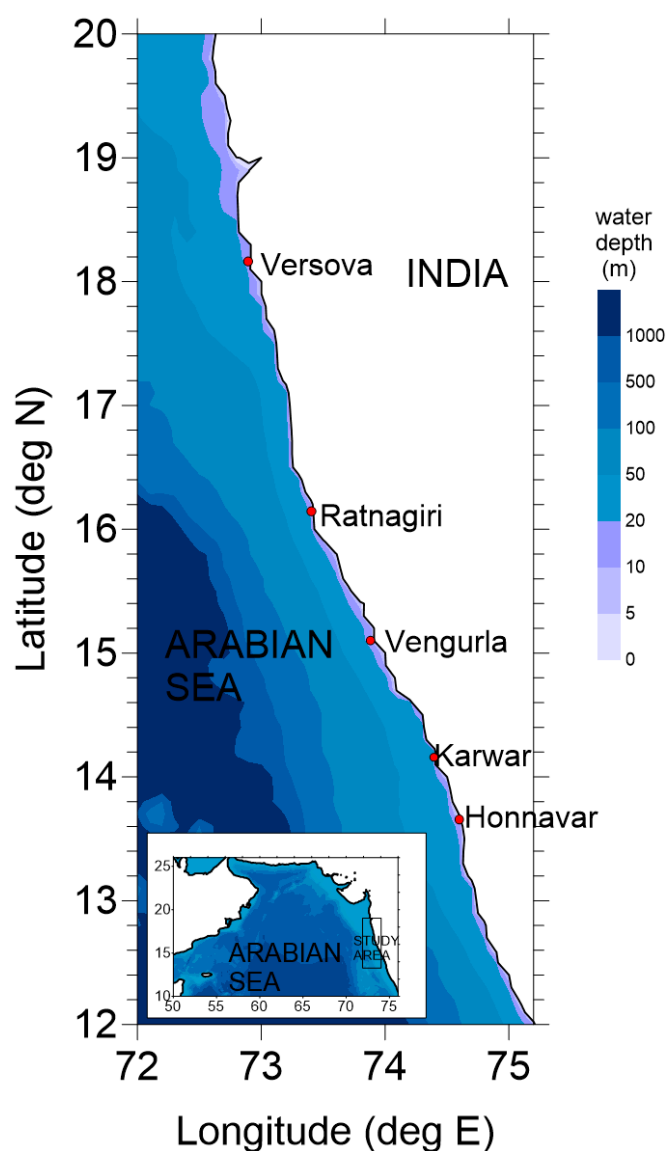


Figure 1. Map showing the study area. The four buoy locations are shown in circle. The colors represent the water depth in meters.

3. Results and Discussion

3.1. Variations in the Monthly Averaged Wave Spectra

The monthly averaged directional wave spectra at Ratnagiri are presented in Figure 2. The data from 2010 to 2020 were averaged for presentation. Two low-frequency signals are

present throughout the year but with varying intensities: one from the S-SW, corresponding to Southern Ocean-generated swell, and another from the SW-W, associated with monsoon swell waves from June to September and swells from the North Indian Ocean.

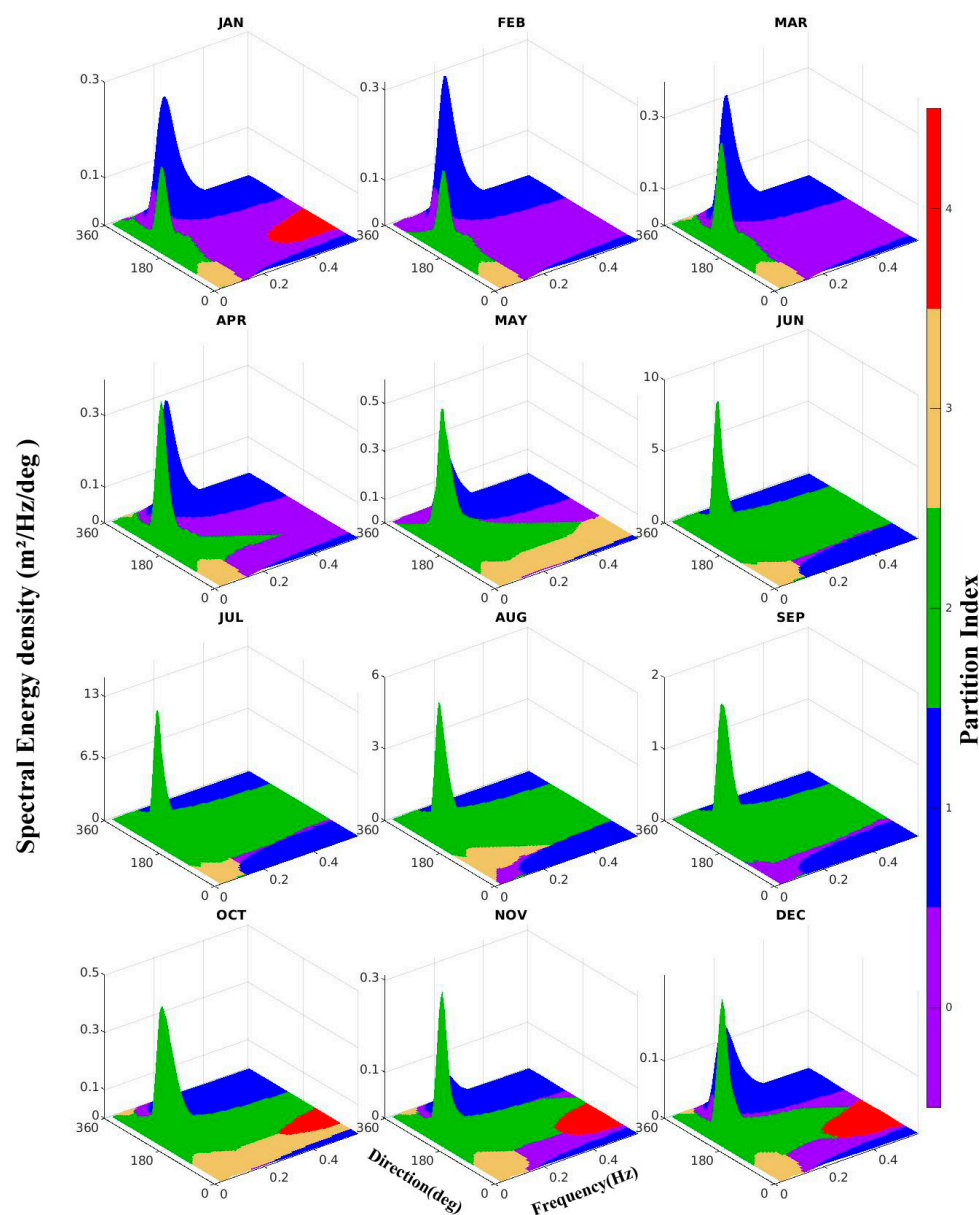


Figure 2. Monthly mean wave directional wave spectra from January to December at Ratnagiri. Data for the period from 2010 to 2020 were averaged. Different wave systems are presented in different colors. Blue is system 1, green is system 2, yellow is system 3, red is system 4 and purple represents unrealistic wave systems, for example those associated with noise in the spectrum.

One higher-frequency signal shifted direction with the seasons, being more NW from February to April and more SW-W from June to August, associated with the local winds. During the monsoon period, the wave spectra were generally single-peaked, and the spectral energy density was within 0.08–0.15 Hz. Waves in the low-frequency region were always from the sector between 210° and 270°, whereas high-frequency waves in the non-monsoon season were from the 270° to 330° sector. During the monsoon, swell-dominated spectra were observed, with peak frequencies less than 0.1 Hz in all years except September, when the peak frequency reached 0.1 Hz, similar to the observations made by Glejin et al. [36].

There was a large difference in wave direction within the frequency range of 0.1–0.2 Hz during the monsoon and pre-monsoon months. Spectral energy was highest during the monsoon season, with the highest value ($25.1 \text{ m}^2/\text{Hz}/\text{deg}$) recorded in July 2019. The coexistence of swells and wind seas was observed during the non-monsoon season, with a swell peak frequency of around 0.07 Hz. In the non-monsoon period, the peak spectral energy density was higher during the pre-monsoon period ($1\text{--}2.8 \text{ m}^2/\text{Hz}/\text{deg}$) than during the post-monsoon period ($0.3\text{--}0.8 \text{ m}^2/\text{Hz}/\text{deg}$).

Four wave systems were identified in the present study throughout the year, except during the monsoons season. System 1, during the non-monsoon period, comes from the NW direction, with a peak at around 0.2 Hz. Most swells occur from 240° to 270° , except swells with a frequency smaller than 0.08 Hz, which vary between 210° and 240° during the monsoon. The low-frequency swells are primarily between 210° and 240° during the non-monsoon season. In the eastern Arabian Sea, using partitioned outputs from WAVEWATCH-III, Amrutha and Kumar [40] observed five wave systems at deeper locations (water depth of $\sim 68 \text{ m}$), whereas the water depth in the present study area was only 13 m.

In January 2014 and 2019, the energy peak of NW swells shifted to $\sim 0.12 \text{ Hz}$ (Supplementary Figures S1a and S1b). A slight ($\sim 5^\circ$) westward shift in the NW swell direction occurred in January 2011, and by 2020, the NW swells' spectral peak energy direction had shifted to 300° . Notably, in February, there was a 5° northward shift in the spectral energy peak of NW swells in 2019 and a westward shift in 2017. In March, the NW wave energy spread extended toward 270° , with peak energy at a frequency of 0.2 Hz. Comparatively reduced spectral energy was observed for NW swells in March 2015. During May, the NW waves' direction varied from 270° to 300° , with the spectral peak shifting to a higher frequency due to the prevailing sea breeze. In November, significant interannual fluctuation occurred in the direction of the NW system ($300^\circ\text{--}330^\circ$), occasionally extending beyond 330° . The local wind changes are primarily responsible for the large interannual variability in the wind sea spectrum observed in May and from September to November [45]. These directional shifts are attributed to changes in the local wind direction, while the frequency shifts result from strong winds at the source location.

In January 2015, swells of higher frequency from the SW had a higher spectral energy peak. While the SW swell energy peak was strong in 2019, only slight interannual variation occurred in the SW swell direction (Figures S1a and S1b). High-frequency swells were seen between 240° and 270° during April every year. With minimal interannual variation, June–August swells dominated in all years. The wind sea during the monsoon occurred from 260° due to a strong SW monsoonal wind pattern causing coastal wind seas to arrive from the WSW. Owing to the intensifying monsoon winds over the southern Arabian Sea and the Indian Ocean, the wave energy moves toward the lower-frequency area. The highest energy occurred in all years between 240° and 270° and between 0.08 and 0.10 Hz. Energy peaks of SW swells appeared near 240° in September 2013 and 2015, as also reported by Glejin et al. [36] in 2011. After September, the spectral peak shifted toward the north. When the spectral energy is low, as in October, it becomes easier to identify the wave systems coming from the NW and SW. During the post-monsoon season, the SW wave system appeared between 210° and 240° . In 2018, there was a 5–10% change in the direction of the SW system. SW systems are more dominant than NW systems during the post-monsoon season.

3.2. Interannual Variation in System-Wise Significant Wave Height

Figure 3 illustrates the system-wise significant wave height (H_s) at Ratnagiri, based on monthly averaged wave spectra. The total H_s exhibits a clear seasonal cycle, with

values ranging from 0.43 m during the post-monsoon season to 2.87 m during the monsoon. System 1 is dominant during the pre-monsoon season, with an average H_s of approximately 0.65 m, slightly higher than in the values for the post-monsoon (0.44 m) and monsoon (0.42 m) periods.

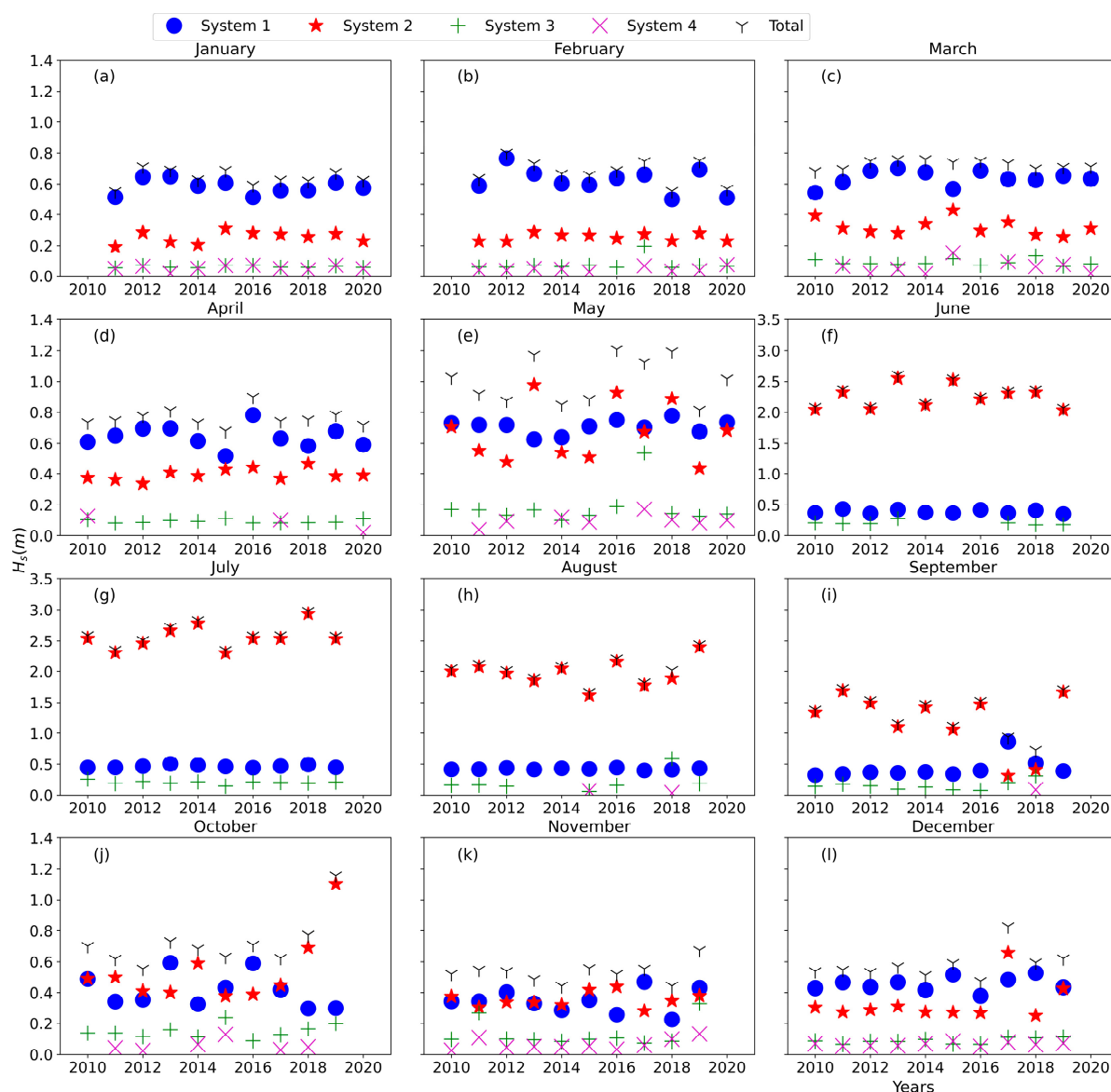


Figure 3. Interannual variation in system-wise significant wave-height at Ratnagiri from 2010 to 2020 during each month from January to December (a–l).

The highest average monthly H_s of system 1 during the pre-monsoon season occurred in May at 0.71 m, while January and March showed averages of 0.57 m and 0.64 m, respectively. System 1's relative contribution to the total H_s was particularly high from January to March, especially in February, where it reached up to 90%, and in January, typically 85%. However, its contribution dropped to 60% or lower in April 2015 (57%) and 2018 (60%), indicating an increasing influence of system 2 during those years. Although system 1 was generally weaker during the monsoon, a notable exception occurred in September 2017, when it exceeded the H_s of the swell system due to high local wind speeds despite the absence of cyclonic activity. Another significant event was observed in November 2017, when system 1's H_s was elevated due to Cyclone Okhi (Figure 3k).

From January to May, system 1 contributes substantially to total H_s , especially in February and March, when contributions reach up to 90%. In February, system 1 contributes between 87 and 90% to the total H_s , slightly higher than the January contribution of around 85%. However, its relative contribution decreases as the monsoon approaches, giving way to system 2. In April 2015 and 2018, system 1's contribution dropped to 57% and 60%, respectively, indicating a seasonal transition in which system 2 began to dominate. System 2 is the dominant system during the monsoon, with an average H_s of 1.99 m and a consistent contribution of ~95% to the total H_s across all years. The maximum H_s of system 2 was observed in July 2018, reaching 2.93 m, while the minimum was 0.19 m in January 2011. During the non-monsoon months, system 2 was typically weak (0.26–0.42 m), but strengthened in May during specific years. February was characterized by enhanced spectral energy from system 2, associated with NW-originating swells in the northern Arabian Sea [37]. These were often linked to Shamal and Makran events, which propagate in two principal directional sectors—from WNW to NNW and from N to NE [33]. During the northeast monsoon and early pre-monsoon periods, prevailing NE winds occasionally weakened, allowing NW winds to intensify over the northwestern Arabian Sea and Arabian Peninsula, leading to enhanced swell propagation in these sectors [37]. As the pre-monsoon season progressed, the spectral peak of these swells gradually shifted westward, occupying a directional band between 300° and 330° . These NW-originating swells typically fell within a frequency range of 0.12–0.25 Hz, and their occurrence in February contributed to the spectral energy enhancement observed at Ratnagiri during that month.

System 1 exhibited limited interannual variability across most months, with notable exceptions in October and May. In January, the system contributed approximately 85% to the total H_s , although this value decreased to 75% in 2011 and 2016, and increased by 10% in 2012. February showed the highest variability, with a 20% increase in 2012 and a 19% decrease in 2018. March 2015 experienced an 11% decline relative to the long-term average. From January to March 2012, system 1 H_s values were consistently elevated, attributed to stronger regional wind conditions [45]. In April, the most prominent anomalies occurred in 2016 (+20%) and 2015 (−19%), while the lowest relative contributions of system 1 to the total H_s (57% and 60%) were recorded in April 2015 and 2018, suggesting enhanced influence of system 2 during those years. Although system 1 typically remained dominant in May, a decrease in its contribution was observed as the season progressed. For instance, in May 2014, a 10% drop in H_s was noted. In contrast, system 2, while generally stable during the monsoon, exhibited modest interannual variability. In August, deviations included a 21% reduction in 2015 and a 25% increase in 2019. September presented the largest fluctuations for system 2, with a 37% increase in 2011 and a 68% decline in 2017. October displayed substantial interannual spread, with peak H_s values recorded in 2018 (+42%), and notably low values in most other years, excluding 2010 and 2011. March 2015 also showed a 37% increase in the H_s of system 2 compared to the climatological average, marking an unusual non-monsoon intensification. Although December is typically less variable, 2017 stands out due to an 80% increase in system 2 H_s associated with Cyclone Okhi. Despite its general weakness in non-monsoon months, system 2's contribution during such extreme events highlights its sensitivity to large-scale wind anomalies and cyclonic influences.

Although systems 3 and 4 contributed relatively little to the total significant wave height (H_s) compared to systems 1 and 2, their presence was non-negligible and varied across seasons. System 3, typically representing secondary swell components, was most evident during the pre-monsoon and post-monsoon periods, particularly in May and October (Figure 3e,j), where it contributed up to ~0.1–0.2 m on average. Its occurrence during monsoon months was limited, likely due to the dominance of strong primary swell systems (System 2) and locally generated wind seas (System 1). System 4 appeared

primarily during pre- and post-monsoon months, with significant contributions in April, May, October, and November (Figure 3d,e,j,k). The H_s of system 4 typically remained below 0.1 m, indicating a short-lived or localized wave component. Notably, both systems 3 and 4 were absent or minimal during peak monsoon months (June to September), when the wave field was largely governed by high-energy swell and wind sea systems. These systems likely represent short-duration or low-energy wave events from distant or transient sources, and while their impact on the overall wave climate is minor, their inclusion helps capture the full complexity of the spectral wave field at Ratnagiri.

3.3. Interannual Variation in System-Wise Peak Wave Period

Figure 4 shows the monthly variation in the peak wave period (T_p) for each wave system at Ratnagiri, derived from the monthly averaged wave spectra.

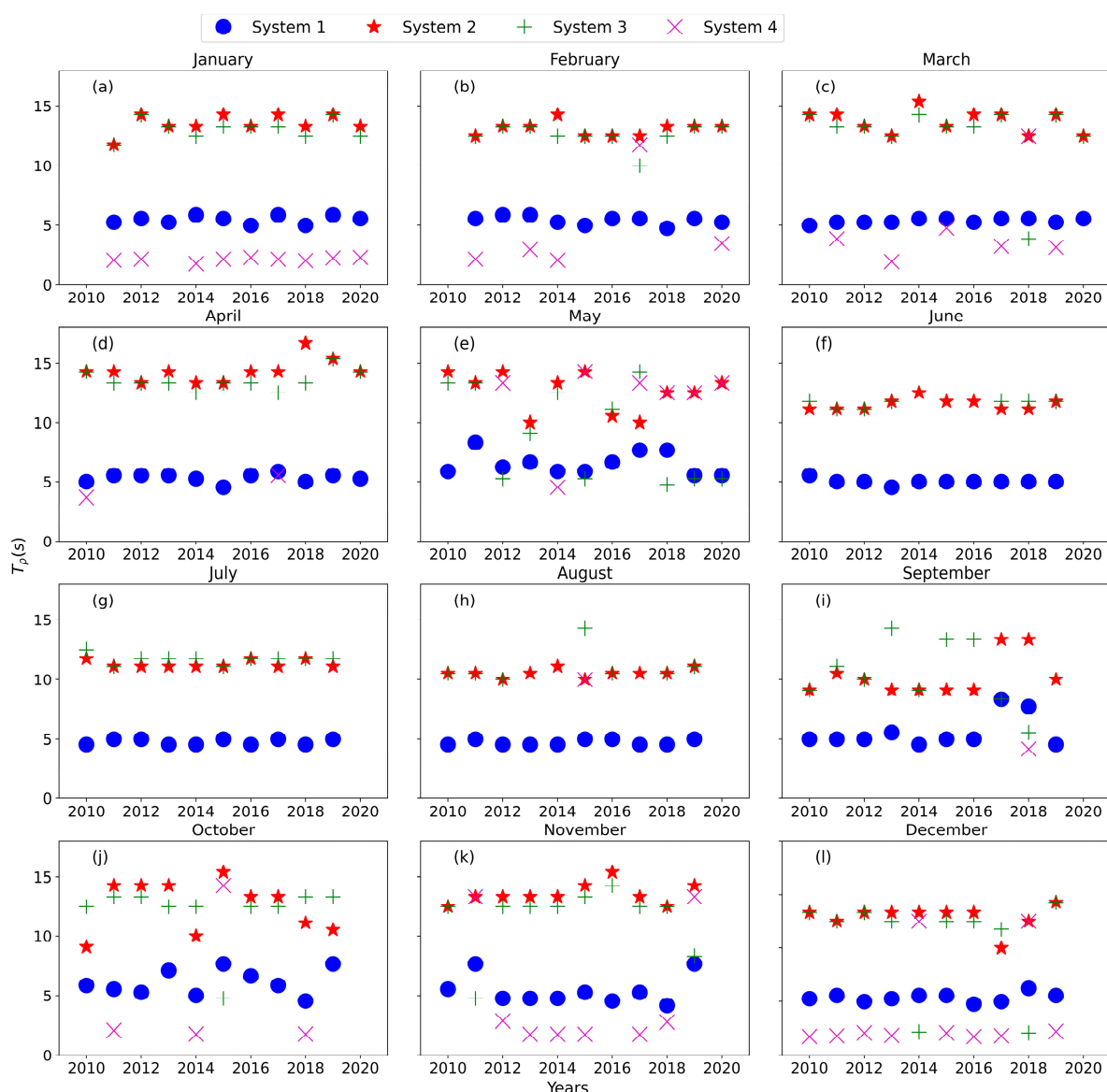


Figure 4. Interannual variation in system-wise peak wave periods at Ratnagiri in each month from January to December (a–l).

System 1 consistently exhibited T_p values below 8.3 s throughout the year, identifying it as a wind sea system with minimal seasonal variation. System 2 was predominantly swell-dominated ($T_p \geq 8.3$ s), particularly during the pre-monsoon season, with T_p typically

between 14 and 16 s. An exception occurred in May, when T_p decreased to 10–12 s but still classified as swell. During the monsoon season (June to September), the T_p values for system 2 decreased further to 9–11 s, maintaining swell characteristics and showing limited seasonal variation. The persistence of long-period waves during the pre-monsoon aligns with previous findings by Amrutha and Kumar [40], highlighting the role of remotely generated swells in this region. System 3 generally exhibited swell characteristics across most months. However, during May in certain years, its T_p dropped below 8.3 s, temporarily behaving as a wind sea. System 4, when present, consistently showed T_p values below 8.3 s, indicating a wind sea system. It was dominant mainly during the pre- and post-monsoon periods, while during the monsoon, swell systems dominated.

System 1 showed limited interannual variability in T_p , with minor deviations primarily in October and November. System 2, while generally stable in most months, exhibited significant interannual variation during the post-monsoon transition months. For instance, in September 2017 and 2018, the T_p of system 2 increased to 14 s and 13 s, respectively (Figure 4i), suggesting more energetic swell conditions in those years. October and November showed the highest year-to-year variation for system 2, with T_p fluctuating between 8.3 and 16 s, particularly in November (Figure 4k). This variability indicates shifting dominance between swell and wind sea influences during the transition period. System 3 also showed notable interannual variation. Although typically swell-dominated, it displayed wind sea behavior ($T_p < 8.3$ s) in May of 2012, 2015, and 2018 (Figure 4e). September and October also reflected considerable year-to-year changes in system 3, including occasional dips into wind sea ranges. System 4 remained predominantly characterized as wind sea across most years, with T_p values consistently below 8.3 s. Isolated exceptions were observed during May, October 2015, and November 2011, but overall, system 4 showed less interannual variability. The greatest T_p fluctuations across systems occurred between September and November, reflecting the dynamic transition between local and remote wave forcing mechanisms during this period.

3.4. Interannual Variation in the Seasonally Averaged Wave Spectrum

Seasonally averaged directional spectra for the years with data for all months were used in this analysis (Figure 5). Swells and locally generated wind seas appeared simultaneously during the non-monsoon period and formed broad-banded wave spectra. In contrast, strong monsoon winds generated narrowly peaked swell spectra.

The interannual variations in the partial H_s and T_p of seasonally averaged spectra are shown in Figure 6. While the monsoon-averaged wave spectra show minimal differences between the years, the seasonally averaged spectra vary considerably between the years during the pre- and post-monsoon periods, which is similar to the observations of Nair and Kumar [45]. In all years during the post-monsoon period and in the 2017 pre-monsoon, four systems were identified. For the monsoon period, three systems were present in 2011 and 2012 and two systems in the remaining years. Shamal and Makran winds and local winds cause system 1, summer monsoon winds cause system 2, and swells from the south Indian Ocean/Southern Ocean cause system 3. Earlier studies have observed double-peaked wave spectra during the non-monsoon season in the eastern Arabian Sea, attributed to the combination of locally generated wind seas and south Indian Ocean swells [40,45]. System 4 is also present during the post-monsoon season, with a period in the SP range. The typical wind sea (system 1) H_s during the pre-monsoon period was 0.66 m, and among all years, 2015 exhibited the most notable decline (−10%), which is also evident in the directional energy spectrum (Figure 5). System 2's H_s averaged 0.42 m, while the 2016 system exhibited the greatest change, with an increase of 31%. While system 2 was the most energizing system during the monsoon, system 1 was the most energizing during

the pre-monsoon period, with a peak frequency of ~ 0.25 Hz. During the monsoon season, the average Hs of system 1 was 0.41 m, and for system 2, it was 1.99 m, with maximum fluctuations of roughly 4% for both systems across all years.

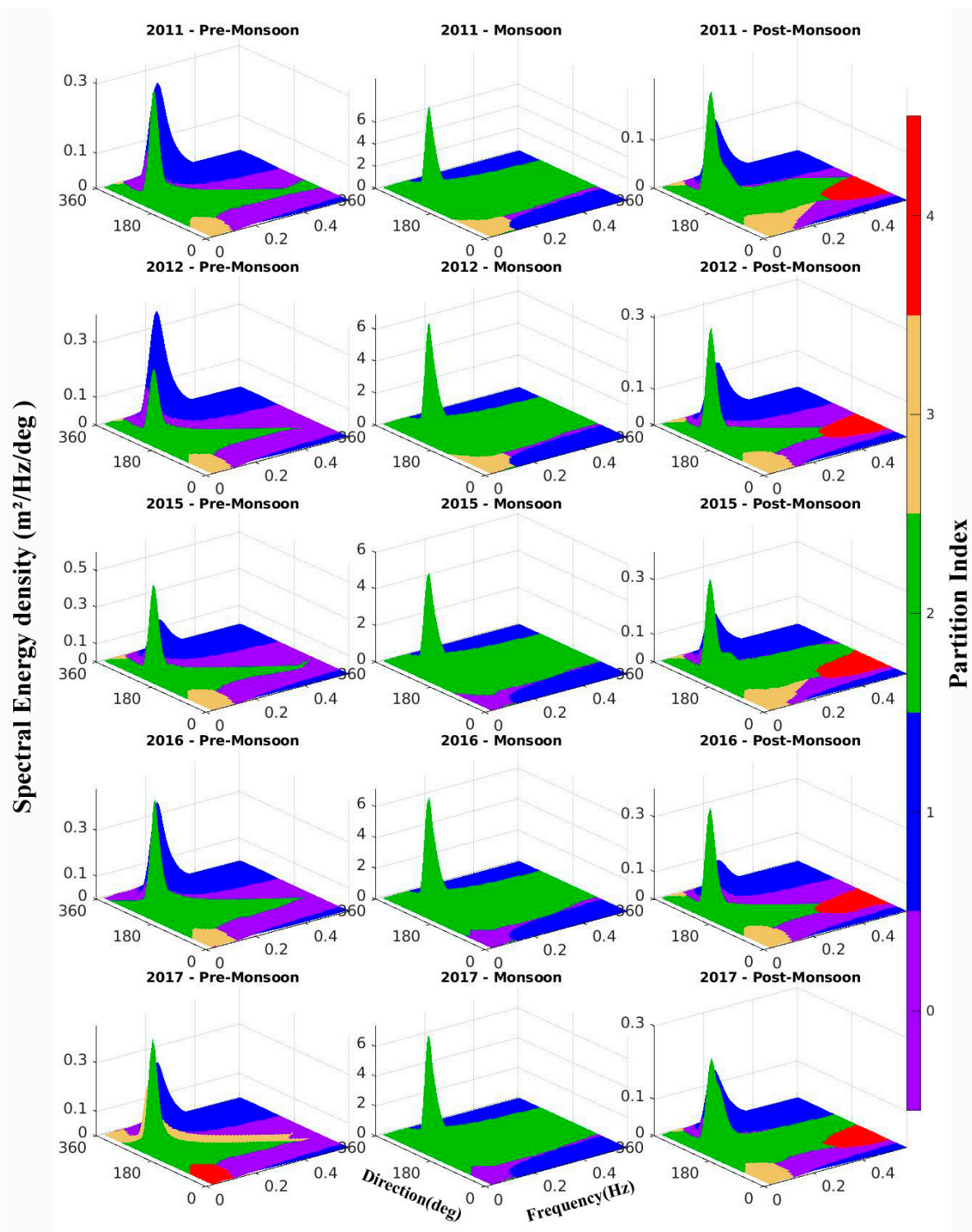


Figure 5. Seasonal (pre-monsoon, monsoon, and post-monsoon) average directional wave spectra for the years 2011, 2012, 2015, 2016, and 2017 at Ratnagiri. Different colors indicate different wave systems as indicated in Figure 2.

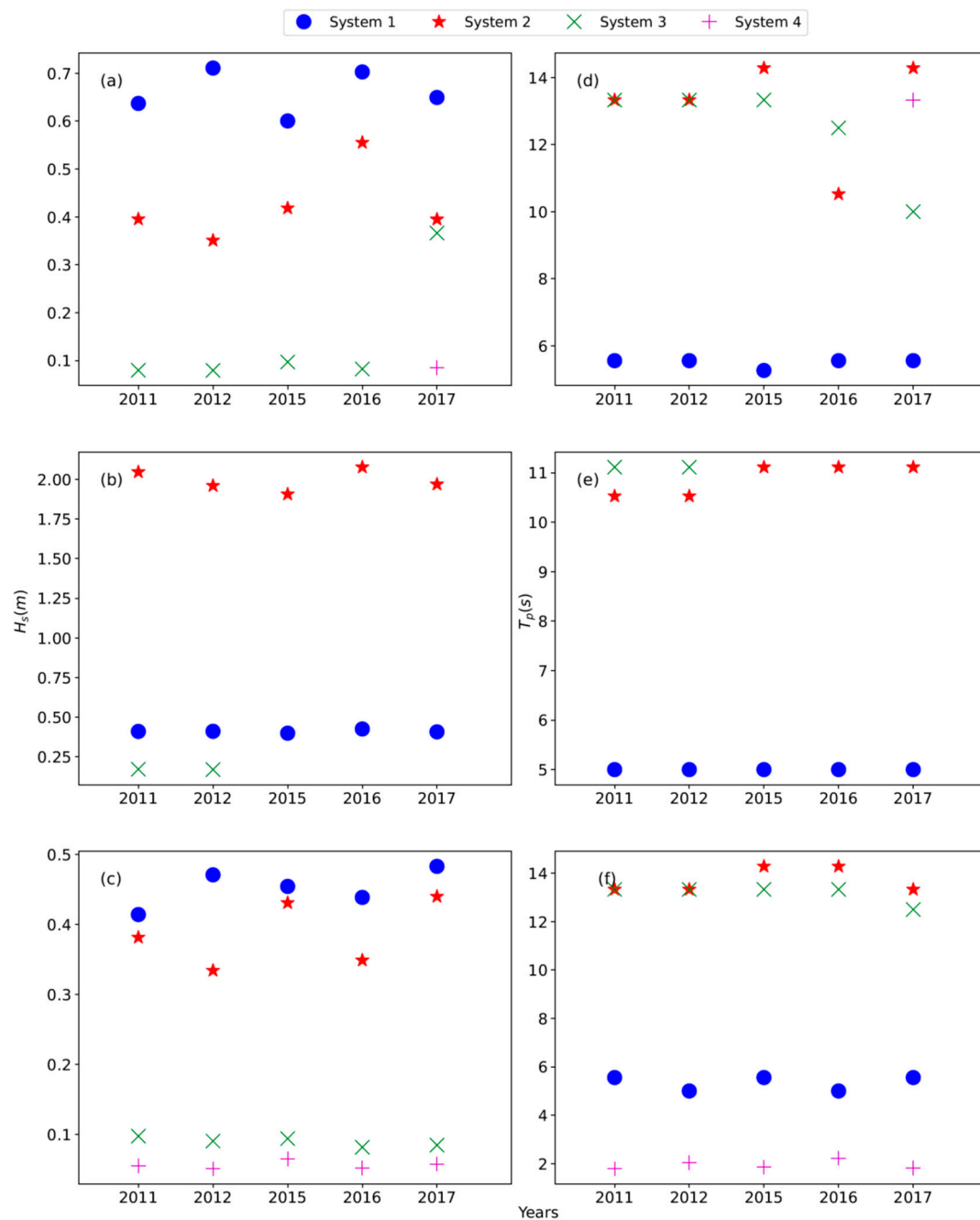


Figure 6. Interannual variation in system-wise significant wave height (a–c) and peak wave period (d–f) during pre-monsoon, post-monsoon, and monsoon seasons for the years 2011, 2012, 2015, 2016, and 2017 at Ratnagiri.

3.5. Spatial Variation in Wave Systems Along the Eastern Arabian Sea

Figure 7 displays the seasonal averaged directional spectra for the year 2017 at another four locations across 570 km along the eastern Arabian Sea. Notably, during the monsoon season, the spectral energy peak was observed from the SW at Versova. Moving southward along the coast, the peak shifts more toward the west. Likewise, during the pre-monsoon season, the systems coming from the NW showed a westward shift moving along the coast.

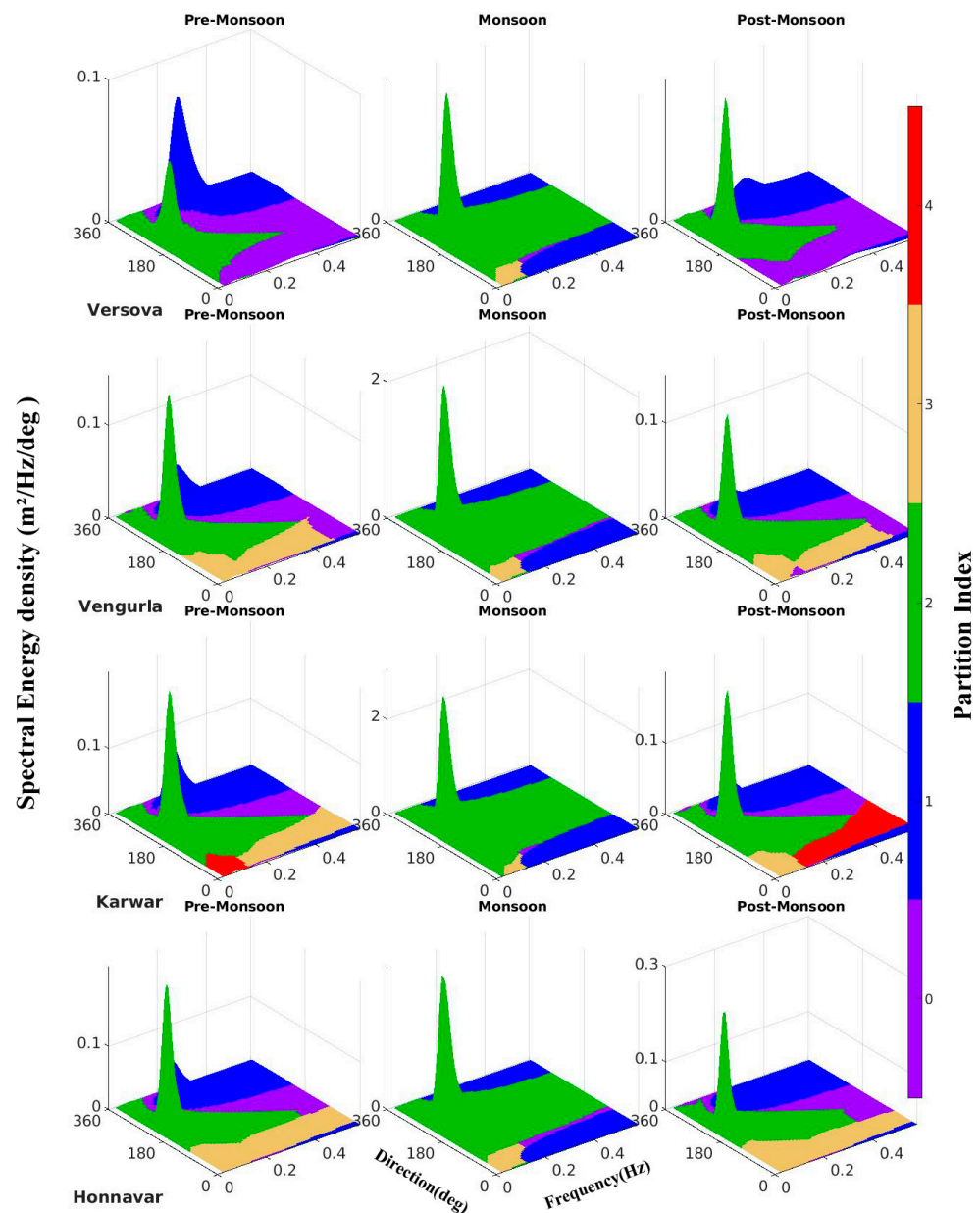


Figure 7. Seasonal (pre-monsoon, monsoon, and post-monsoon) average directional wave spectra at Versova, Vengurla, Karwar, and Honnavar for the year 2017. Different colors indicate different wave systems as indicated in Figure 2.

Partitioning of the seasonally averaged directional spectra at four locations along the west coast was performed to investigate the spatial variations in different wave systems. Throughout that year, up to four wave systems were recorded, with the highest wave height (2.8 m) observed at Karwar during the SW monsoon and the lowest (0.39 m) at Versova in the post-monsoon period. During the monsoon season, all locations experienced three wave systems, while during the pre- and post-monsoon periods, only two systems were present at Versova. System 1, characterized as a short-period wave system, exhibited significant variations among the locations in the non-monsoon periods compared to the monsoon. System 1 dominated during the pre-monsoon period at all locations, while system 2 dominated during the monsoon. In the post-monsoon period, both systems 1 and 2 occurred with nearly equal intensity at all locations. System 1 was the primary contributor to the total H_s , accounting for 80% at Versova and over 50% at other locations

during the pre-monsoon period. However, during the post-monsoon period, it remained the largest contributor to the total H_s only at Versova and Ratnagiri (Figure 8).

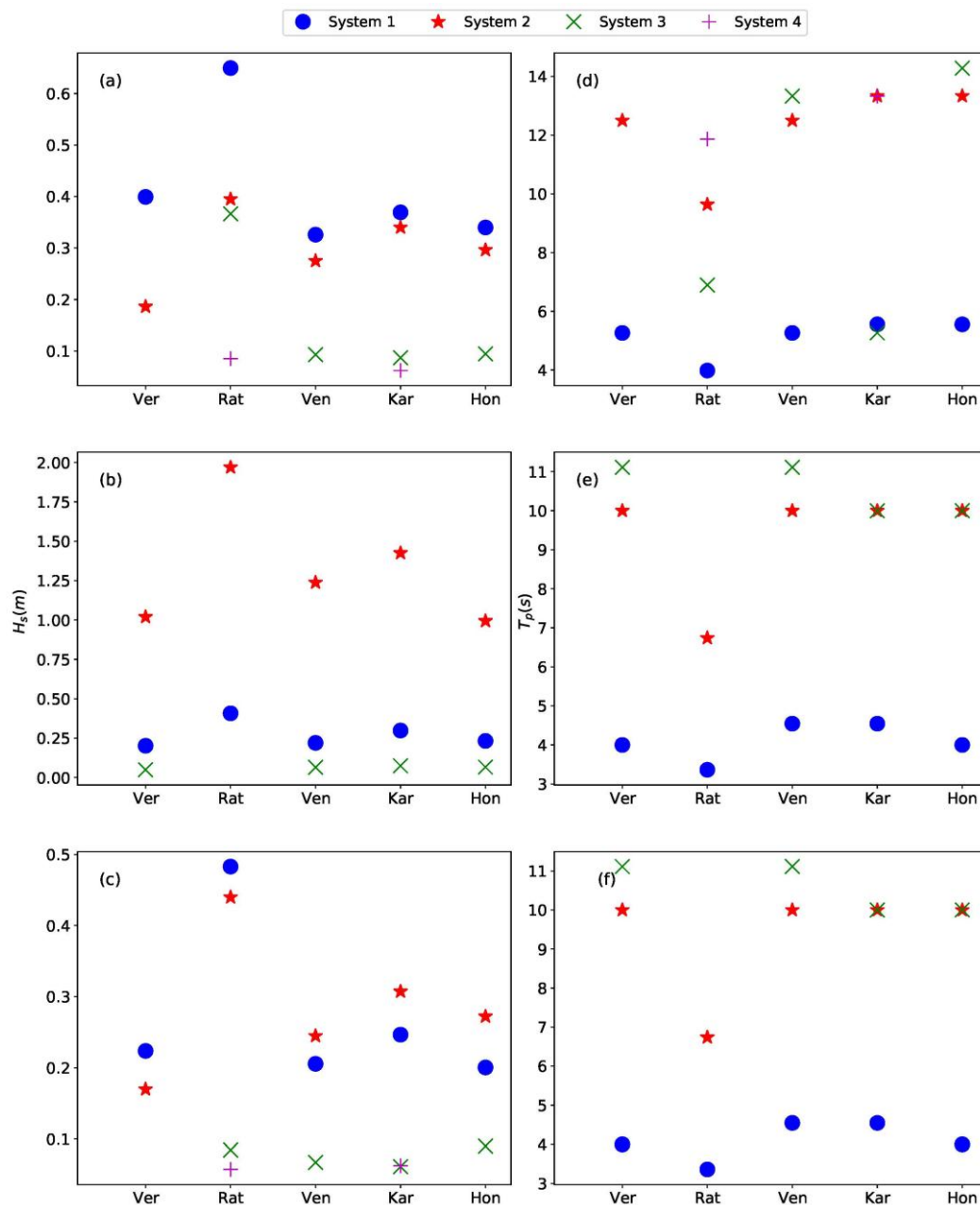


Figure 8. Spatial variation in system-wise significant wave height (a–c) and peak wave period (d–f) during pre-monsoon, post-monsoon, and monsoon seasons for the year 2017 at Versova (Ver), Ratnagiri (Rat), Vengurla (Ven), Karwar (Kar), and Honnavar (Hon).

System 2 mainly consisted of intermediate period (IP) waves, reaching its highest H_s (1.96 m) at Karwar during the monsoon and its lowest in the post-monsoon period at Versova. It contributed to over 95% of the total H_s during the monsoon at all locations and during post-monsoon period, except for Versova and Ratnagiri. During the monsoon, system 3 comprised intermediate period waves, shifting to short-period waves in the pre-monsoon period. It was absent at Ratnagiri during the monsoon but present at all other locations. System 4 was only found at Ratnagiri and Karwar, characterized as intermediate during the pre-monsoon period and as a short-period during the post-monsoon period.

Both systems 3 and 4 were relatively minor, with their partial H_s to total H_s generally below 5%, except for system 3 at Ratnagiri during the pre-monsoon period.

4. Discussion

The multimodal nature of wave regimes in the eastern Arabian Sea, as revealed through spectral partitioning of buoy data, highlights the complex interplay between local wind forcing and remotely generated swell fields. The differentiation of four coexisting wave systems during the non-monsoon season and three during monsoon months reflects the influence of both regional synoptic circulations and trans-oceanic wave propagation. The dominance of system 1 (wind seas from NW) during the pre-monsoon period is consistent with seasonal sea breeze activity, while the pronounced swell signature from SW during the monsoon period (system 2) is consistent with swell generation driven by persistent Findlater Jet winds.

The pronounced interannual variability observed in May and October suggests that such transitional periods are sensitive to shifts in wind patterns, including anomalies linked to Shamal and Makran events. These episodes result in modifications to both peak wave periods and spectral energy orientation, indicating transient swell arrivals or local intensification of wind seas. The appearance of system 4 (short-period waves) during post-monsoon months is likely associated with local wind bursts or residual turbulence following cyclone decay, such as the signal associated with Cyclone Okhi in November 2017.

Spatial variations among the five buoy locations reveal directional refraction effects and geographic modulation. For instance, spectral peaks from NW tend to rotate westward with decreasing latitude, pointing to a combination of bathymetric steering and regional wind realignment. Although the buoy sites are located in shallow water (9–15 m), the directional integrity of the 2D spectra remains consistent enough to retain system-level signatures, validating the robustness of the partitioning technique despite refraction-induced distortions.

The distinction between swell and wind sea systems based on peak wave period and spectral separation criteria adds precision to operational applications. For offshore structural design, the separation of dominant swell systems from transient wind sea events helps in load condition assessments and berthing alignment. Moreover, the identification of minor wave systems (systems 3 and 4), although energetically less significant, is crucial for event-scale predictions, particularly during post-monsoon transition and pre-cyclonic states.

Overall, this discussion amplifies the need for multivariate approaches in wave climatology that consider frequency–directional spectra, seasonality, and interannual anomalies. Future efforts could benefit from coupled spectral wave wind modeling, incorporating advanced reanalysis datasets and machine learning-based pattern recognition to automate wave system tracking.

5. Concluding Remarks

This study was based on measured waverider buoy data covering ten years at a 13 m water depth in the eastern Arabian Sea and one year of data at other four locations covering a spatial distance of 570 km. A total of four wave systems were observed during the non-monsoon period and three systems during monsoon months. During the monsoon season, the WSW direction was where the strongest systems with H_s mean values greater than 2.5 m appeared. The two months with the largest interannual fluctuations in monthly average partial H_s and T_p were the inter-monsoon months, i.e., May and October. The interannual monthly fluctuation of H_s in system 1 exhibited a similar trend in all monsoon

months during every year, but it was comparatively higher in September 2017. During the post-monsoon season, system 4 presented a period in the short-period range. Wind seas (system 1) dominated in the pre-monsoon period, while swells (system 2) dominated in the monsoon period in the coastal waters of the eastern Arabian Sea. In the western coastal waters of India, Shamal and Makran winds, along with local winds, caused one system, summer monsoon winds caused another system, and swells from the south Indian Ocean/Southern Ocean caused the third system. Spatial comparisons across five sites revealed consistent spectral shifts, highlighting the influence of both local winds and remote forcing mechanisms, such as Shamal and Makran winds.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/oceans6030053/s1>, Figure S1a: Monthly mean wave directional wave spectrum from March 2010 to December 2015 at Ratnagiri. The white patch indicates the month in which data is less than 90%. The spectral energy density ($\text{m}^2/\text{Hz}/\text{deg}$) is in logarithmic scale. The concentric circles represent 0.1, 0.3 and 0.5 Hz frequencies; Figure S1b: Monthly mean wave directional wave spectrum from January 2016 to May 2020 at Ratnagiri. The white patch indicates the month in which data is less than 90%. The spectral energy density ($\text{m}^2/\text{Hz}/\text{deg}$) is in logarithmic scale. The concentric circles represent 0.1, 0.3 and 0.5 Hz frequencies.

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