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Monsoon and cyclone induced wave climate over the near shore waters off Puduchery, south western Bay of Bengal

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Abstract

Seasonal and annual variations in wave characteristics are studied based on measurements during 2009-2011 using wave rider buoy. Presence of swells generated by the south Indian Ocean cyclones are found over the south western Bay of Bengal during pre monsoon season. Maximum significant wave height is measured 6 m during Thane cyclone in December 2011. Long period waves are observed mostly during the summer (SW) monsoon and are negligible in the winter (NE) monsoon period. Short period waves dominate (63%) the wave climate during the NE monsoon. Wave spectra during the SW monsoon are multi peaked whereas during the post monsoon season single peaked spectra are found. Single peaked spectra observed during SW monsoon of 2011 coincides with the presence of positive Indian Ocean Dipole. Waves during the pre monsoon and SW monsoon season are influenced by sea breeze. Analysis indicates that directional width is minimum for waves from the NE since they are wind waves and maximum for waves from SE since they are swells. Study indicates that wave climate of the south western Bay of Bengal is in contrast to that in eastern Arabian Sea during the SW monsoon.

Key words: wind sea, swell, directional width, sea breeze, wave spectrum

Introduction

Winds blowing over the sea surface generate wind waves due to the energy exchange between the atmosphere and the sea. Generation and growth of the waves depend on the wind speed, fetch and duration. Waves that have been generated elsewhere and had travelled far away distances from their place of origin becomes swells. Ocean waves are irregular and multi-directional due to the superimposition of many monochromatic wave components of different frequencies, amplitude and directions. Bay of Bengal (BoB) experiences three different weather conditions; i) fair weather / pre monsoon (February - May), ii) south-west (SW) / summer monsoon (June - September) and north-east (NE) / post monsoon (October - January). During the fair weather season, sea is usually calm and the coastal region is dominated by swells and to a smaller extent by locally generated waves. Extreme weather events are common during the SW monsoon and NE monsoon seasons. The east coast of India experience a number of low pressure systems and 5 to 6 tropical cyclonic storms per year originate from BoB and the frequency and intensity these storms have increased recently (Mohapatra and Mohanty 2004; Singh 2001).

East coast of India is characterized by narrow continental shelf width compared to the west coast. Simpson et al. (2006) reported the presence of sea breeze system over the east coast of India. Influence of the sea breeze on the wave characteristics along the west coast of India are studied by different authors (Glejin et al. 2012; Neetu et al. 2006) and are not attempted for the east coast of India. Wave characteristics over the western BoB are studied based on measured data covering few months to one year (Kumar et al. 2002; Mishra et al. 2011; Suresh et al. 2010). The wave spectra along the Indian coast are generally multi-peaked (Harish and Baba 1986; Kumar et al. 2003; Rao and Baba, 1996) and occurrences of double-peaked spectra are more frequent during the low sea states. Wave spectra along the east coast of India during extreme events are single-peaked (Aboobacker et al. 2009; Kumar et al. 2004) and occurs when spectral peak period for fully developed sea equals peak wave period (Torsethaugen and Haver 2004).

Two of the major offshore fields in India are located in the Krishna-Godavari basin and Cauvery basin, along the east coast of India, in the Bay of Bengal (Petromin 2010). So it is important to know the variation in wave climate over the south eastern coast of India. Besides the seasonal and extreme wind conditions over the BoB produces changes in waves climate and the nature of the seasonal variability along the south western BoB is not well described. All earlier studies carried out over the BoB on waves are restricted for a short period or for a particular season. Accordingly we studied the characteristics of wind sea and swell off Puduchery along the south western BoB based on the measured data using directional wave rider buoy during 2009-2011. Since directional spreading of sea states is an important design parameter, we have also studied the variation of directional spreading parameter. In addition, the influence of sea breeze on the wave characteristics is also examined.

2. Data and Methodology

Wave observations off Puduchery, south western BoB (Fig. 1) during 2009 to 2011 are made using a directional wave rider buoy (Barstow and Kollstad 1991) at location 11° 55’ 26” N : 79° 51’ 03” E for the study. Measurement location is off the east coast of India. Data analysis is done as below, similar to the one described in Glejin et al. (2013). The displacement data are recorded continuously at 1.28 Hz and the data for every 30 minutes are processed as one record. At every 200 s, a total number of 256 heave samples are collected and a Fast Fourier transform (FFT) is applied to obtain a spectrum in frequency range 0 to 0.58 Hz having a resolution of 0.005 Hz. Eight consecutive spectra covering 1600 s are averaged and used to compute the half-hourly wave spectrum. Significant wave height (H_{m0}) or $4\sqrt{m_o}$ is obtained from the wave spectrum. Here, m_n is the nth order spectral moment and is given by $m_n = \int_0^\infty f^n S(f) df$, n=0, S(f) is the spectral energy density at frequency f. Period corresponding to the maximum spectral energy (i.e., spectral peak period (Tp)) is estimated from the wave spectrum. Wave direction (Dp) and directional width corresponding to the spectral peak are estimated based on circular moments (Kuik et al. 1988). Measurements are made in Coordinated Universal Time (UTC) and the time referred in the paper is in UTC. The local time is 05:30 hrs ahead of UTC. Wind seas and swells from the measured data are separated through the method described by Portilla et al. (2009). Portilla et al. (2009) proposed a 1-D separation algorithm based on the assumption that the energy at peak frequency of a swell system cannot be higher than the value of a PM spectrum (Pierson and Moskowitz 1964) with the same peak frequency. The algorithm calculates the ratio (γ^*) between the peak energy of a wave system and the energy of a PM spectrum at the same frequency. If γ^* is above a threshold value of 1, then the system is considered to represent the wind sea; otherwise, it is taken to be swell and a cutoff frequency f_c is estimated. The swell parameters are computed by integrating frequency ranging from 0.025 Hz to f_c and the wind sea parameters are computed by integrating frequency ranging from f_c to 0.58 Hz.

Reanalysis data, NCEP / NCAR (Kalnay et al. 1996), provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado at http://www.cdc.noaa.gov/ at 10 m height with a temporal resolution of 6 hour intervals is used to analyze the wind pattern. The meteorological convention is used for presenting the wind and wave direction data (0 and 360° for wind/wave from North, 90 for

East, 180 for South, 270 for West). Nature of the wave is identified and classified based on steepness parameter, G_R ($G_R = Hm_0 / L$) into i) sea ($0.083 < G_R < 0.025$), ii) young swell ($0.025 < G_R < .01$), iii) mature swell ($0.01 < G_R < 0.004$) and iii) old swell ($G_R < 0.004$) based on Thompson et al. (1984). Where L is the wave length calculated for spectral peak period (Tp).

3. Results and discussion

3.1 Wave classification

For understanding of seasonal and annual wave climate, waves are classified into three categories based on the spectral peak period (Glejin et al. 2012); (1) short period waves (Tp < 8 s), (2) intermediate period waves (8 < Tp < 13 s) and (3) long period waves (Tp > 13 s).

3.1.1 Short period waves

Short period waves are observed during 50% of the time in three years period with 59% of time during the pre and NE monsoon season (Fig. 2) due to the domination of wind seas and young swells produced by the NE monsoon and local sea breeze system from the NE and SE direction. Direction of these short period waves (Fig. 3) is mainly from SE in post monsoon season whereas during SW monsoon, the direction of propagation is from east. During the pre monsoon season, short period waves are a minimum because of the calm wind condition prevailing over the BoB and this type of wave are with H_{m0} in the range of 0.2 - 2 m and T_{m02} from 2.4 to 7 s.

3.1.2 Intermediate period waves

Intermediate period waves are observed for 45% of time during the study period (Fig. 2). Direction of these waves are from SE during all seasons due to the propagation of young and mature swells from the north and south Indian Ocean from the tropical south Indian ocean generated by the strong easterlies (Fig. 4). Intermediate period waves are associated with H_{m0} in the range of 0.2 - 6 m and T_{m02} from 2.5 to 9.3 s.

3.1.3 Long period waves

Long period waves are observed for 5% of time during the study period (Fig. 2). Presence of long period waves are observed maximum during October (13%) followed by July, August and September (8%) in the SW monsoon season whereas long period waves are negligible (< 1%) during December and January. This is due to the propagation of westward swells generated in the southern ocean south of Australia due to the weak summer storms and intense winter storms (Alves 2006). These types of waves show a common direction of propagation from the SE and are dominated by the presence of mature swells propagating from the south Indian Ocean and have H_{m0} in the range of 0.4 – 0.9 m and T_{m02} from 2.7 to 8.7 s. As Alves (2006) reported, storms within extra tropical south Indian ocean typically propagate to the east, below 40° S (Fig. 4). Maximum storm densities occur on the western sides of these ocean basins near 50° S. Waves generated by these winds propagates towards eastern side of BoB, as it moves towards and observed along the west coast of India (Glejin et al. 2013).

3.2 Influence of sea breeze and land breeze on waves

Fig. 5 depicts the hourly variation of H_{m0} in 2009 off Puduchery. Analysis indicates similar variation in 2010 and 2011. Simpson et al. (2006) studied the presence and variation of sea breeze over the east coast of India during the summer monsoon period and showed that sea breeze system is most active during the month of June followed by July and August. Wind direction during the early morning hours are westerly (from 260°) and around 02:30 hrs UTC (08:00 LT) the wind direction changes to southerly due to the sea breeze. Wind direction is around 140° by 06:30 hrs UTC (12:00 LT) when the sea breeze is well developed. Southeasterly winds are observed throughout the afternoon until 11:30 hrs UTC (17:00 LT), when the wind direction begins to shift to southerly as the sea breeze weakens. Wind speeds are about 2.5 m/s until the sea breeze starts developing at 02:30 hrs UTC (08:00 LT). Maximum wind speed (≈ 5 m/s) is observed around 07:30 hrs UTC (13:00 LT) and wind speed steadily decreased throughout the afternoon and is around 2.6 m/s by 14:30 hrs UTC (20:00 LT).

In the summer monsoon months, increase in wave height is observed during the afternoon. Increase in wind sea and corresponding change in the total wave height is maximum during June and the changes decrease gradually during June to September. Change in wave height is also observed during the pre monsoon season. Maximum wave height (0.74 -1.04 m) is observed between 17:00 and 18:00 hrs (UTC) and minimum (0.53 - 0.72 m) during 10:00 hrs (UTC) during this period. Fig. 5 shows that swell height is steady during each month and the total wave height changes with change in wind sea generated due to the local sea breeze. The estimated time lag between maximum wind speed and resultant maximum wave energy spectrum is around 5-6 hours. The time lag is due to the time taken by the waves to reach its maximum wave growth (Neetu et al. 2006) and the change in wave height due to sea breeze observed during June is up to 0.3 m calculated from difference between total and wind sea height. During the post monsoon season (NE monsoon) minimum wave height (0.45 - 0.84 m) is observed at 05:00 hrs UTC.

3.3 Inter annual variability in wave characteristics

Wave data is analyzed to understand the seasonal and annual variation in wave characteristics. The study area is dominated with waves having H_{m0} in the range of 0.75 to 1.5 m during 80% of time and out of which about 40% of waves is in 1–1.25 m range and 20% of waves is in the range of 0.75-1 m and 1.25-1.5 m (Fig. 6). Occurrence of Tp shows wind sea dominated and swell dominated spectra with Tp in the range of 6-7 s and 10-11 s. Maximum Tp observed is in the range 18-19 s with fewer occurrences and 70% of waves is with Tp below 11 s. During an annual period, 90% of the waves approach either from SE or ESE and the remaining are from the ENE direction. The predominant direction of waves is 120-140°.

Inter-annual variability of principal wave components (Fig:7 a-c), significant wave height (H_{m0}), peak wave period (Tp) and mean wave direction, shows variation throughout the study period. Seasonally, monthly mean H_{m0} are greatest in the post monsoon months from November through February. Mean H_{m0} are generally smaller in the summer months, compared to post monsoon months. Monthly H_{m0} values of more than 1 m are most frequent in the post monsoon month of December. But a secondary peak in wave height is evident with H_{m0} less than 1 m during the summer monsoon season. Maximum H_{m0} (6 m) during the entire record is in December 2011 and is caused by the cyclone Thane. Peak swells occurs seasonally in the summer and pre monsoon months and minimum during the post monsoon months. Mean wave direction indicates propagation of swells predominantly from the E and SE direction during the summer and pre-monsoon season rather than NE direction during the post monsoon season. NE waves are dominated by the wind sea produced by the NE monsoonal winds and local sea breeze. Trend analysis for the three-year period indicates an increasing trend in significant wave height and peak wave period.

3.4 Wave spectrum

Monthly averaged wave spectrum is calculated from the spectra obtained during half hourly interval for studying the spectral characteristics (Fig 8). The study shows that the post monsoon season (NE monsoon) is characterized by single peaked wave spectra in the wind sea or short period range. The presence of peak in the swell band during the season is due to the cyclones/storms occurred during the period (Table 1). Rest of the season is characterized by the double peak spectra due to the locally generated wind sea (sea breeze) and propagation of intermediate and long period swells towards the north Indian Ocean. The broadening of spectrum and presence of single peak during SW monsoon months of July, August and September of 2011 coincides with the presence of positive Indian Ocean Dipole (IOD) during the year 2011 (JAMSTEC).

3.5 Variation of sea state over Bay of Bengal due to cyclones

Variation in wave climate off Puduchery is studied to assess the change in wave climate due to the cyclonic activity over the BoB and long period waves generated by strong winds in the Southern Ocean region south of Australia (Alves 2006). Indian Daily Weather Report (Anonymous 1996) reveals the presence of 16 storms / depressions (Table 2) in the BoB during the study period. Near-shore off the coast of Puduchery is affected by seven major cyclones out of the sixteen cyclonic activities during 2009 and 2011 (Table 2 and Fig. 1). The pressure level data from the Cyclone Detection Radar Centre indicates that maximum pressure drop of 52 hpa and maximum wind speed of 105 knots for the cyclone GIRI during 20-23 October 2010 (Table 1) and minimum for cyclone BIJLI (8 hpa and 40 knots respectively) during 14-17 April 2009.

Presence of north Indian Ocean swells are also found in the study area during the post and pre monsoon period. Presence of cyclone generated waves in the BoB is identified by the domination of swell parameter and sudden increase in significant and maximum wave height. Extreme wind condition occurred due to the tropical cyclones over the study area shows extreme wave condition (Alves 2006). Highest maximum (8 m) and significant wave height (6 m) is observed during the Thane cyclone. Wave period associated with the north Indian Ocean cyclones are in the intermediate period. Maximum H_{m0} observed in 10 m water depth at 130 km south of the study area is 1.8 m (Kumar et al. 2002). Mishra et al. (2011) reported maximum H_{m0} of about 2.85 m over western BoB during summer monsoon in 2008.

Tropical cyclone THANE is formed on 25 December 2011 as a Tropical Depression and weakened on 30 December 2011 (Chu et al. 2012). During Thane cyclone (25-29 December 2011), the spectral energy density varied from 1 to 85 m^2/Hz (Kumar et al. 2013). Wave spectra is predominantly broad banded during 20-25 December with energy spreading from 0.1 to 0.3 Hz and during cyclone period (26-29 December), the spectra is narrow banded with spectral energy concentrated between 0.07 and 0.14 Hz (Kumar et al. 2013). Severe Cyclonic Storm JAL formed as a depression and intensified as severe cyclonic storm on 6 November 2010. Crossed north Tamil Nadu and south Andhra Pradesh coast close to north of Chennai near 13.3 deg N 80.2 deg E around 1600 UTC of 07 November 2010. Attained maximum wind speed 30 m/s and minimum pressure of 988 hPa at 1200 UTC of 06 November 2010. During the Jal cyclone (04 - 08 November 2010), the spectral energy density varied from -0.14 to 18.8 85 m^2/Hz. H_{m0} increased from 0.5 to 2.5 m due to the influence of cyclone Jal.

Presence of swells produced by the southern Indian Ocean cyclones is observed in pre monsoon season during the months of January (Vince 2011), February (Freddy 2009), March (Lisa 2009) and April (Robyn 2010). These swells propagate westward from the tropical south Indian Ocean and show an impact in the south western BoB. Alves (2006) also observed similar pattern of swell propagation from Tropical South Indian Ocean to Tropical North Indian ocean. Maximum and minimum H_{m0} associated with these swells is 0.75 m during category 4 tropical cyclone Lisa and 0.2 m during category 1 tropical cyclone Freddy. South Indian Ocean waves generated by these tropical cyclones west /North-West of Australia propagates into the study area with peak wave period (Tp) in the range of 8.3 and 12 s and reach the study area with a time lag of 4-6 days during different cyclones.

3.6 Directional spreading of waves

Directional spread of measured waves for different wave types (short period, intermediate period and long period waves), seasons (pre monsoon, SW monsoon and post monsoon) and wave types based on wave steepness (Sea, young swell, mature swell and old swell) are analyzed. As expected directional spreading of waves show an increasing trend with increase in Tp (Table 3). Seasonal variation of mean directional width (directional spreading parameter) is minimum during 2010 (25.9-27.1°) and 2011 (24°- 26.3°) than that during 2009 (23.8-30.1°). Analysis also indicate that directional width is minimum for waves from the North East direction (wind waves) and are maximum for waves from South East (swells) due to the open ocean towards south and land boundary restriction over the north and north eastern side of Puduchery. Mean directional width for the sea and young swell over the region shows less variation. Mean directional width shows an increasing trend for old swells (decrease in wave steepness). Analysis indicates that slight variation of wave age is in direct relationship with the directional width. Young (1994) indicated slight increase in directional width as wave age decreases. Standard deviation of directional width shows an increasing trend from sea to old swell over the region off Puduchery. The directional width for high waves (H_{m0} > 2 m) is less with average value of 18.4° compared to the annual average of 26.3°. The study indicates a decrease in directional spread with increase in wave height similar to that reported by Kumar (2006).

3.7 Domination of wind sea over south western BoB

Near-shore wave climate will depend on the combined effect of both locally generated wind seas and remotely generated distant swells. Analysis of wave data by separating into wind sea and swell indicate the influence of local wind systems and remote wind influence over the near-shore regions. Fig. 9 depicts the domination of wind sea over swells during most of the time. Domination of both wind sea and swell is observed during the month of July, August, September and October (mainly during the SW monsoon season). Dominance of swells during these months are due to the swells from the SE direction from the south Indian ocean. Swells from the NE and south are restricted due to the land area cover over the north by the parts of Indian subcontinents and Sri Lanka at the south of the measurement location. Variation in wind sea and swell over the day during March to October is due to the active sea breeze system present over the east coast of India. Absence of variation in wind sea and swell during the months of NE monsoon is due to the active monsoonal winds generated wind sea domination (Table 2). During the SW monsoon season the winds from the SW has less influence on the wave climate and is dominated by swell during the morning hours and by wind sea during night due to the sea breeze. This indicates that wave climate over the south western BoB is in contrast to the wave climate over the eastern Arabian Sea during the SW monsoon. Over the eastern Arabian Sea, during the SW monsoon, the swell dominance is observed and sea breeze is absent (Aboobacker et al., 2011; Glejin et al., 2012; Kumar et al., 2003; Neethu et al., 2006). Wind sea domination is observed during the pre and post monsoon period with wind sea and swells balancing each other during the SW monsoon season (Table 4). Waves over the south western BoB are mainly dominated by the young swell and old swell (Table 5). Wind sea is observed least in the three-year period with an average value of 9.3%.

4. Conclusion

Wave data collected off Puduchery during 2009 - 2011 are used to analyze the seasonal and cyclone induced wave climate over the south western Bay of Bengal. The analysis indicates the presence of waves from NE and SE due to wind sea and swells produced by NE monsoon winds and the wind systems in the South Indian Ocean. During the pre monsoon and SW monsoon period, the near-shore wave characteristics is a function of SE winds associated with sea breeze over the region and reaching maximum at midday (07:30 UTC) whereas over the eastern Arabian Sea, sea breeze influence is not found during the SW monsoon period. Presence of long period waves are observed with low wave height mainly during the pre and SW monsoon season and these waves are from SE direction and originated in the South Indian Ocean and the Southern Ocean. During the SW monsoon season, presence of sea breeze and SE swells from the south Indian Ocean contributes to the double peaked wave spectrum. Increase in wave height caused by the sea breeze is maximum during the month of June in the SW monsoon season. During the SW monsoon season, the domination of wind sea and swell are almost in equilibrium condition due to the sea breeze generated wind sea and swell from the SE direction. Wind sea domination is observed during the calm pre monsoon and rough post monsoon season. Hourly variation of wind sea and swell over a day is minimum during the SW monsoon season.

Broadening of spectrum and presence of single peak during SW monsoon months of July, August and September coincides with the presence of positive Indian Ocean Dipole during the year 2011. Waves generated by the cyclonic activities play an important role in the wave climate during the pre and post monsoon season with extreme wave conditions. A decrease in directional width is found with increase in wave height.

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Table 1 Major cyclones over Bay of Bengal, North Indian Ocean during 2009 and 2011 (CS: Cyclonic Storm SCS: Severe Cyclonic Storm VSCS: Very Severe Cyclonic Storm)

Cyclones	Date	year	Maximum wind (knots)	Maximum pressure drop at the centre (hpa)	Grade
BIJLI	Apr 14-17	2009	40	8	CS
AILA	May 23-26	2009	60	20	SCS
WARD	Dec 10- 15	2009	45	10	CS
LAILA	May 17-21	2010	55	15	SCS
GIRI	Oct 20-23	2010	105	52	VSCS
JAL	Nov04-08	2010	60	18	SCS
THANE	Dec 25-31	2011	75	30	VSCS

Table 2 Depression/cyclone activity in BOB during 2009-2011 (D: Depression DD: Deep depression CS: Cyclonic Storm SCS: Severe Cyclonic Storm VSCS: Very Severe Cyclonic Storm SuCS: Super Cyclonic Storm)

year	D	DD	CS	SCS	VSCS	SuCS	Total
2009	0	2	2	1	0	0	5
2010	2	1	0	2	1	0	6
2011	2	2	0	0	1	0	5
Total	4	5	2	3	2	0	16

Table 3 Directional spreading of waves in degrees during 2009-2011

year	class	Wave classification			Monsoon Seasons			Wave type			
	statistics	Short	Inter	Long	Pre	SW	Post	Sea	Young	Mature	Old
2009	Min	9.1	8.4	18.9	10.4	8.4	10.1	12.1	8.4	9.6	10.9
	Max	58.9	74.1	79.8	79.8	72.1	74.1	58.9	58.9	61.50	79.8
	Mean	22.9	28.7	45.0	30.1	23.8	25.8	21.9	22.8	25.8	33.9
	Std	5.9	8.2	11.6	9.5	8.7	6.7	5.3	5.8	6.4	10.4
2010	Min	10.4	8.1	15.8	10.5	10.4	8.1	12.9	8.1	10.5	12.1
	Max	72.3	76.0	75.0	75.0	76.0	75.5	41.6	54.4	76.0	75.5
	Mean	22.0	30.1	44.8	27.1	27.5	25.9	22.4	21.5	26.5	33.9
	Std	5.0	9.0	12.1	10.1	9.6	7.9	4.4	5.0	7.1	10.5
2011	Min	9.2	7.9	16.0	9.2	9.2	7.9	12.0	9.2	7.9	11.6
	Max	52.3	71.5	76.2	71.5	76.2	75.5	47.1	52.3	53.2	76.2
	Mean	21.9	27.5	44.2	26.3	24.0	26.3	23.1	21.2	24.0	35.2
	Std	5.3	9.1	11.5	8.2	10.1	9.6	5.5	5.0	6.6	11.5

Table 4 Wave type observed during different years

year	season	Wind sea (%)	Swell (%)
2009	Pre	0.35	0.65
	Mon	0.47	0.53
	post	0.35	0.65
2010	Pre	0.24	0.76
	Mon	0.51	0.49
	post	0.42	0.58
2011	Pre	0.31	0.69
	Mon	0.46	0.54
	post	0.35	0.65

Table 5 Nature of the sea state according to wave steepness

Year	Sea	Nature of the sea state (%)		
		Young swell	Mature swell	Old swell
2009	8	36	29	27
2010	10	34	24	32
2011	10	41	24	25
Average	9.3	37	25.7	28

Figure captions

Fig. 1: Study area and wave measurement location along the south western Bay of Bengal. Tracks indicates the cyclones in Bay of Bengal during 2009, 2010, and 2011. The depth contours are in meters.

Fig. 2: Composite monthly variations in percentage occurrence of short period waves (Tp < 8), Intermediate period waves (8 <Tp<13), and long period waves (Tp >13) during 2009, 2010, and 2011.

Fig. 3: Seasonal variations in wave direction of short period waves during (a) pre monsoon, (b) SW monsoon and (c) post monsoon, intermediate period waves during (d) pre monsoon (e) SW monsoon and (f) post monsoon, and long period waves during (g) pre monsoon (h) SW monsoon and (i) post monsoon

Fig 4: Annual composite of wind speed and direction over the western side of northern and southern Indian ocean. Wind speed is in m/s.

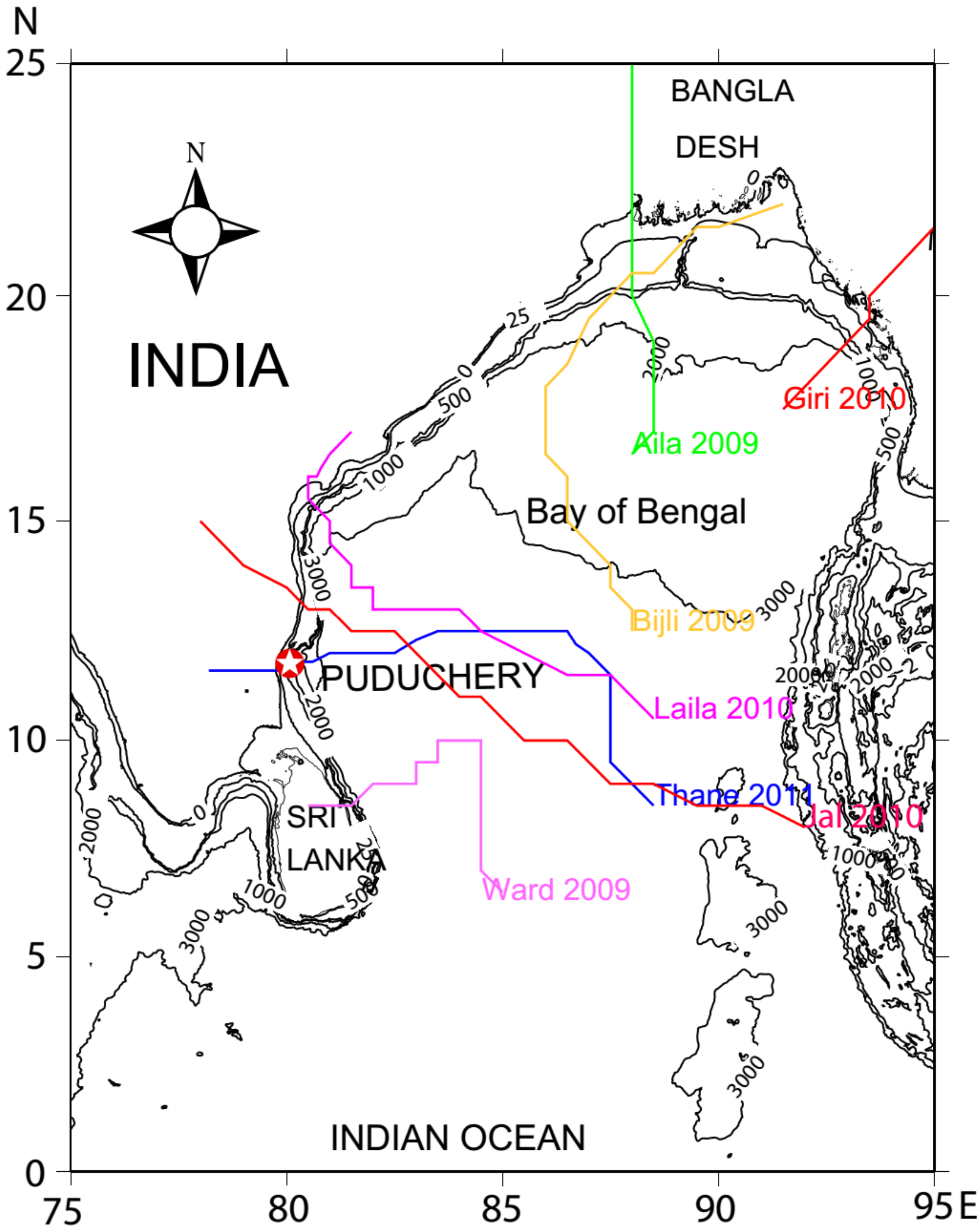
Fig. 5: Hourly variation of monthly average significant wave height (sea, swell and total) during different months in 2009. X-axis represents time in UTC

Fig. 6: Variation in percentage occurrence of (a) significant wave height (H_{m0}) in meters, (b) peak wave period (Tp) in seconds, and (c) wave direction (Dp) in degrees during 2009, 2010, and 2011

Fig. 7 Weekly average of (a) significant wave height (H_{m0}) in meters, (b) peak wave period (Tp) in seconds and (c) wave direction(Dp) in degrees during 2009 - 2011. X-axis represents the time period in months

Fig. 8: Plots of monthly average spectral density of measured waves off Puduchery, during 2009, 2010, and 2011

Fig. 9: Hourly variation of wind sea and swell domination in percentage during a day averaged over three years in different months. X-axis represents time in UTC



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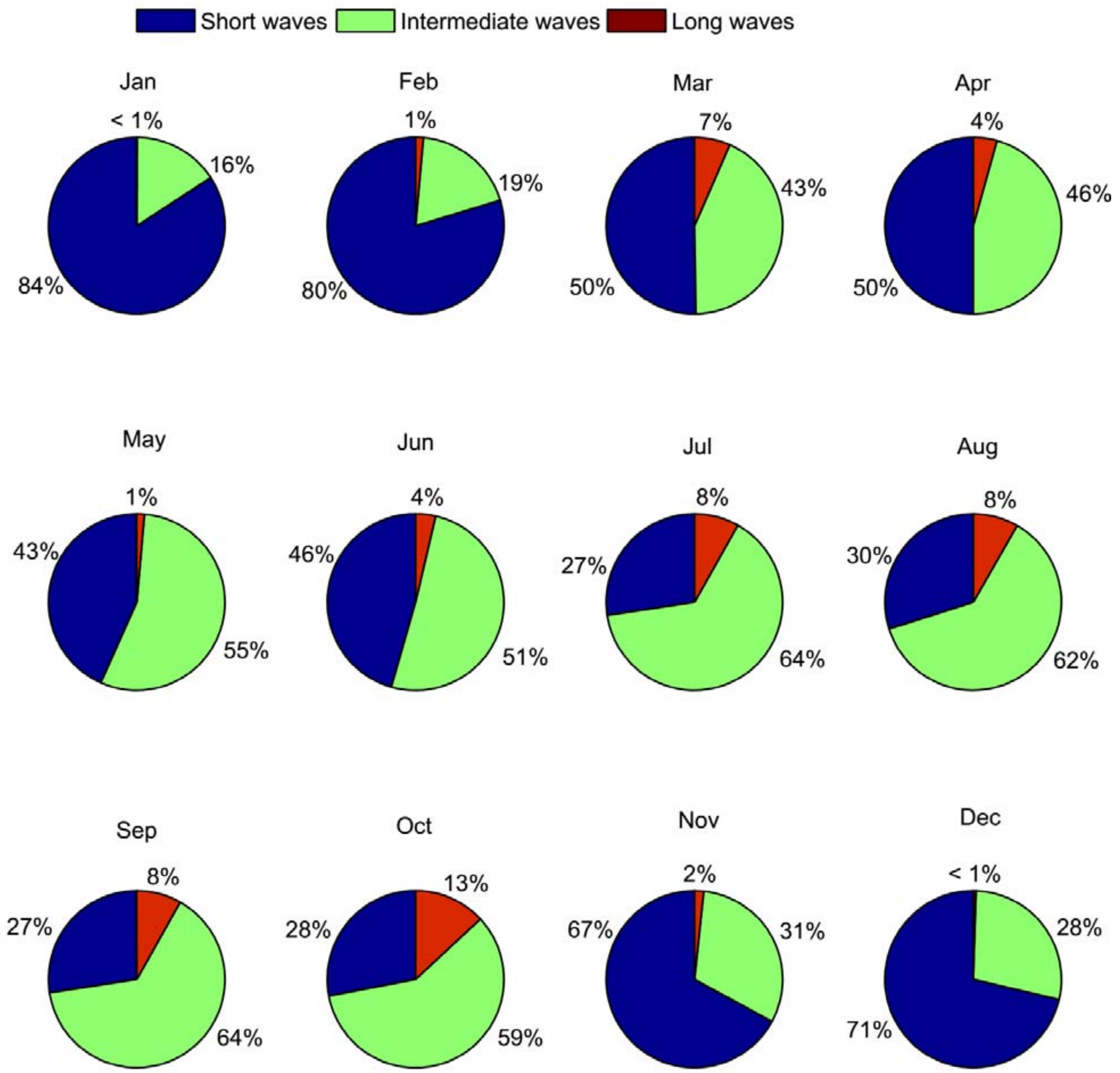

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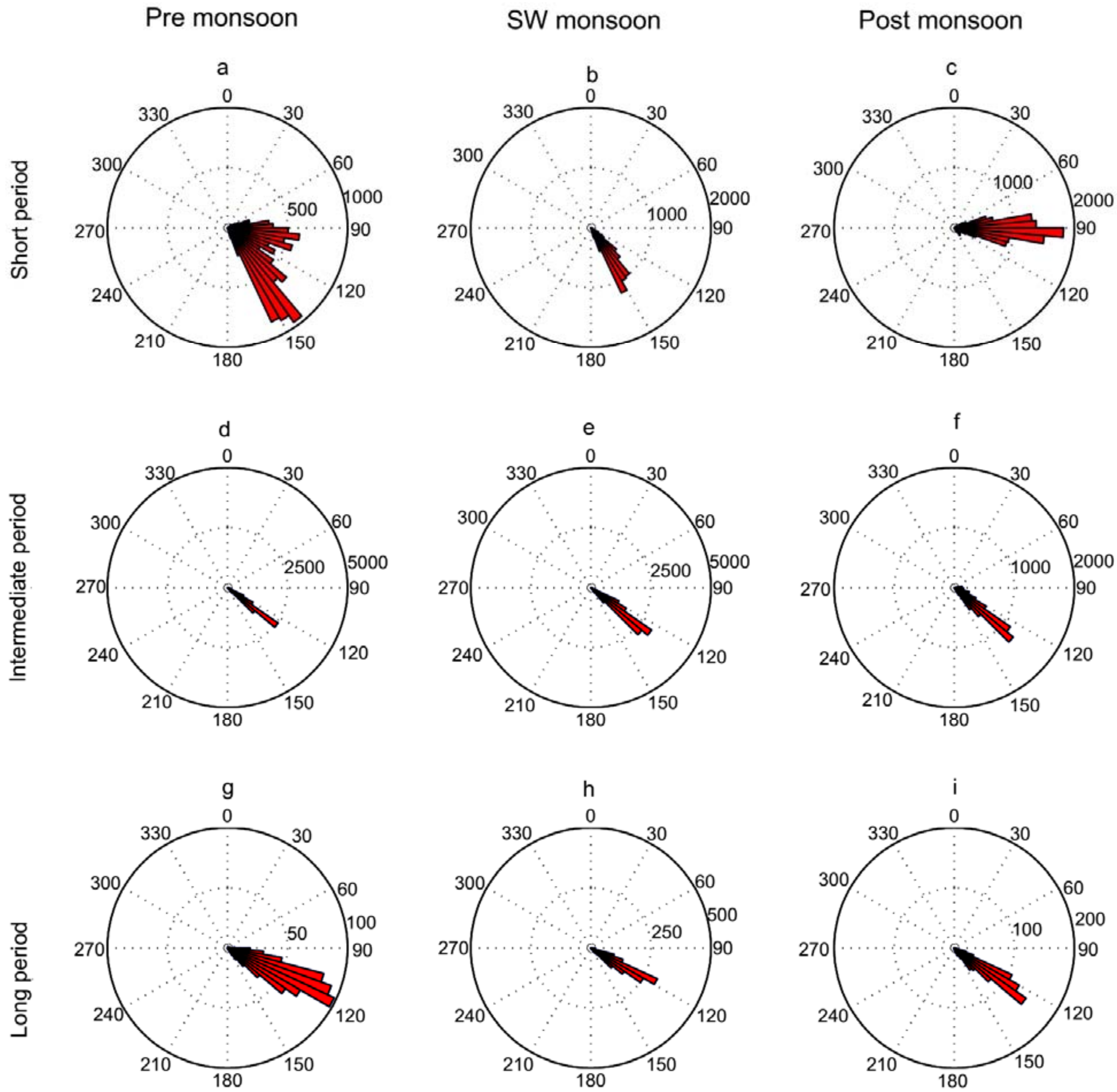

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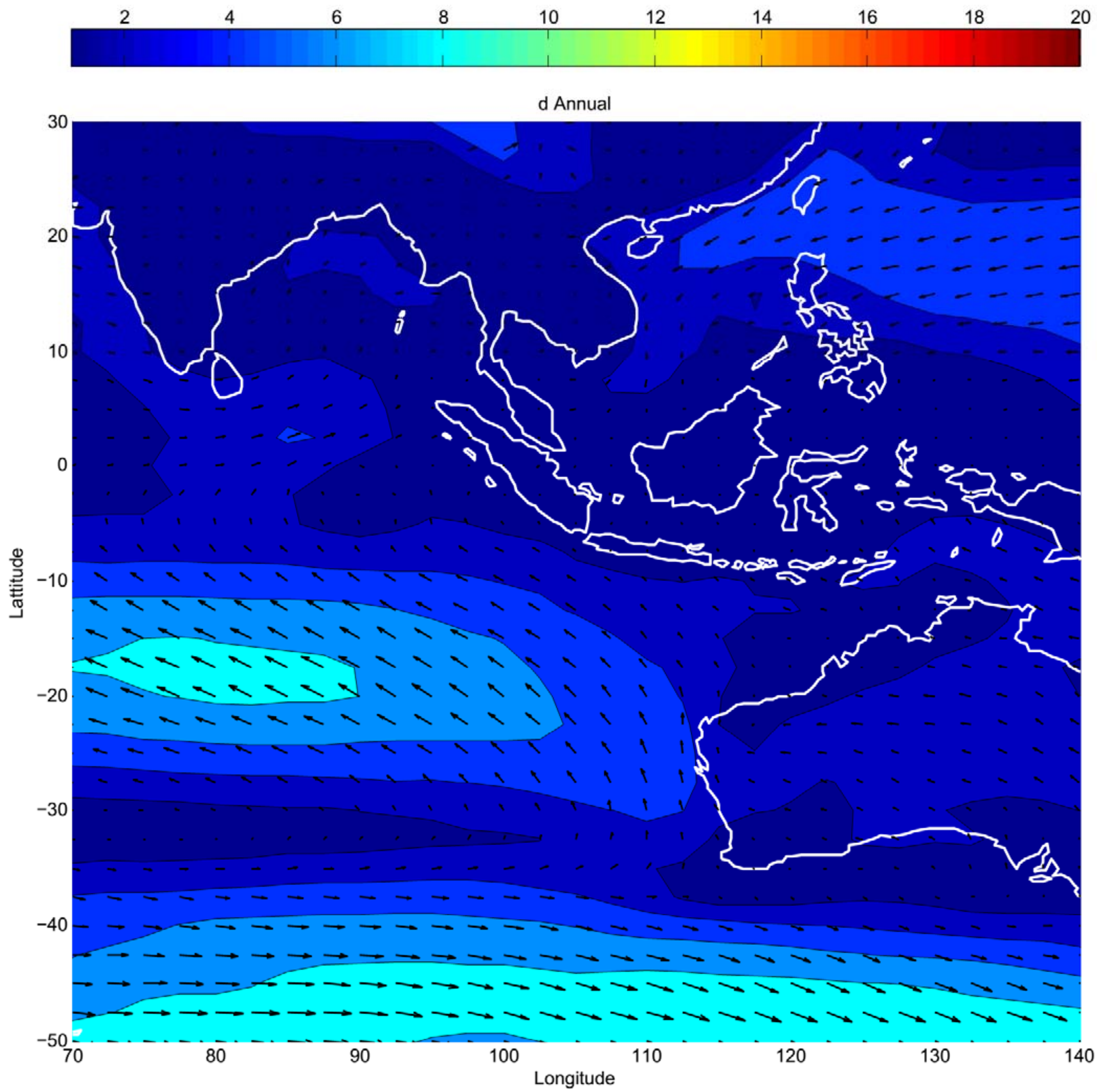

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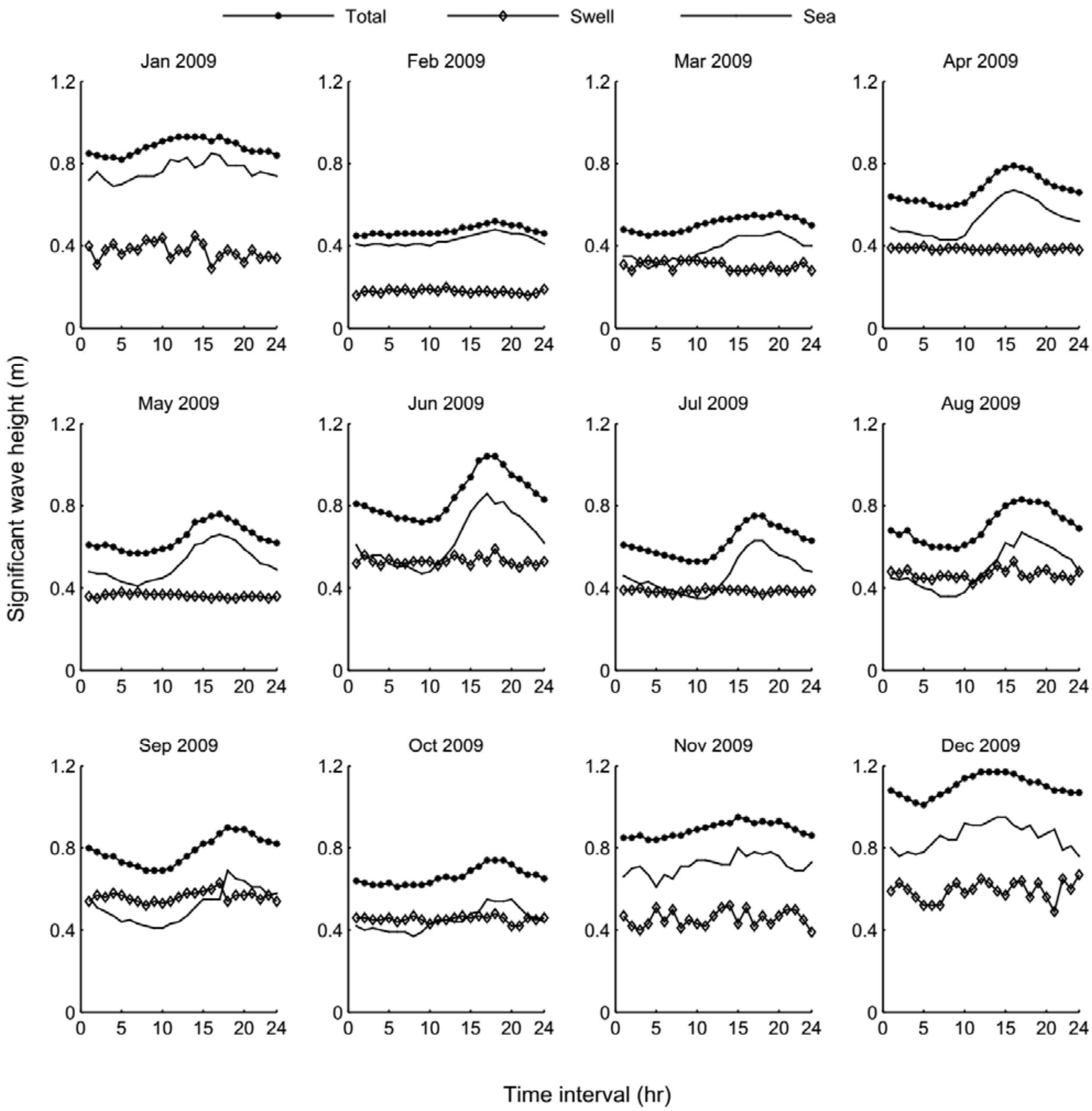

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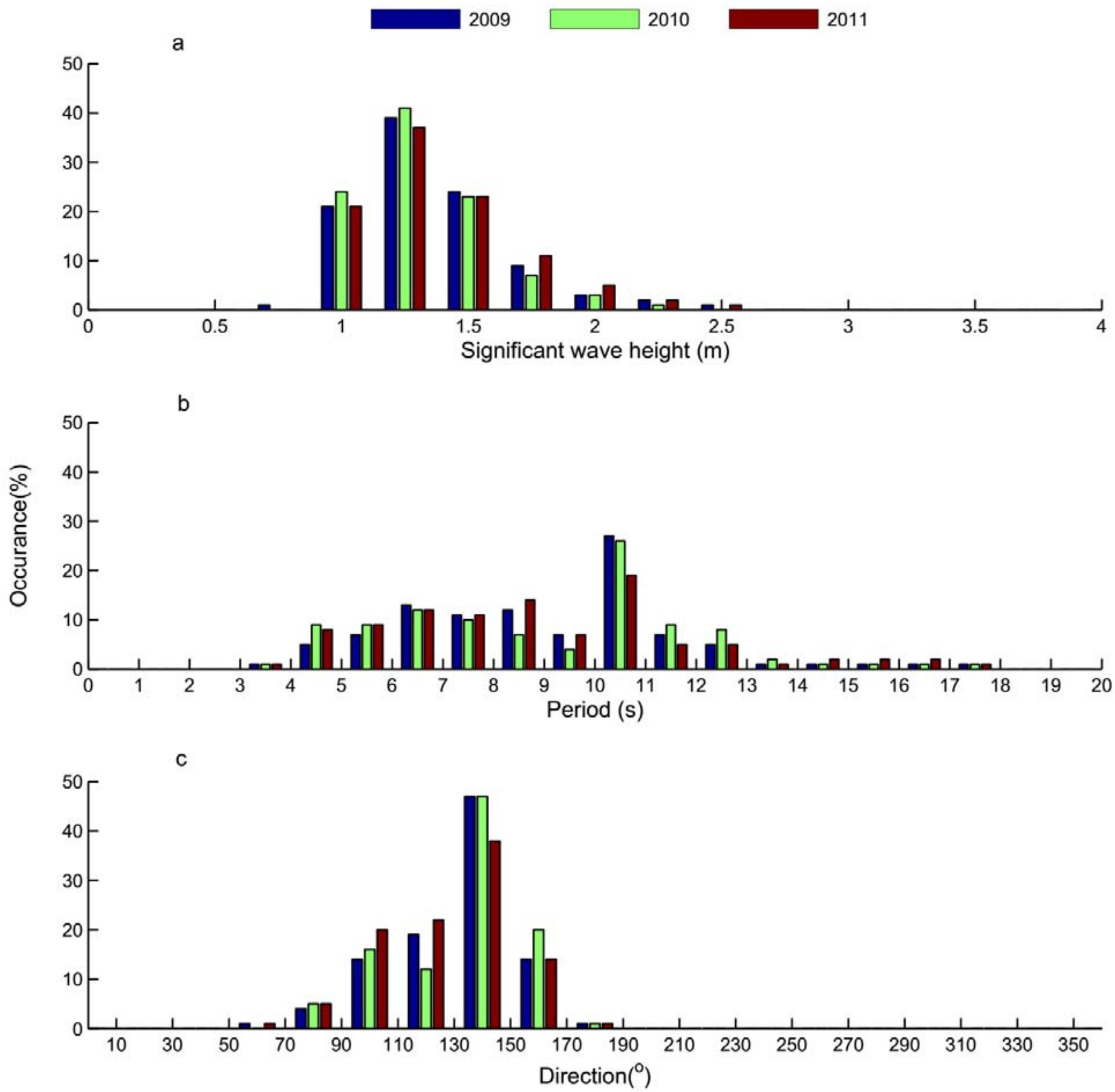

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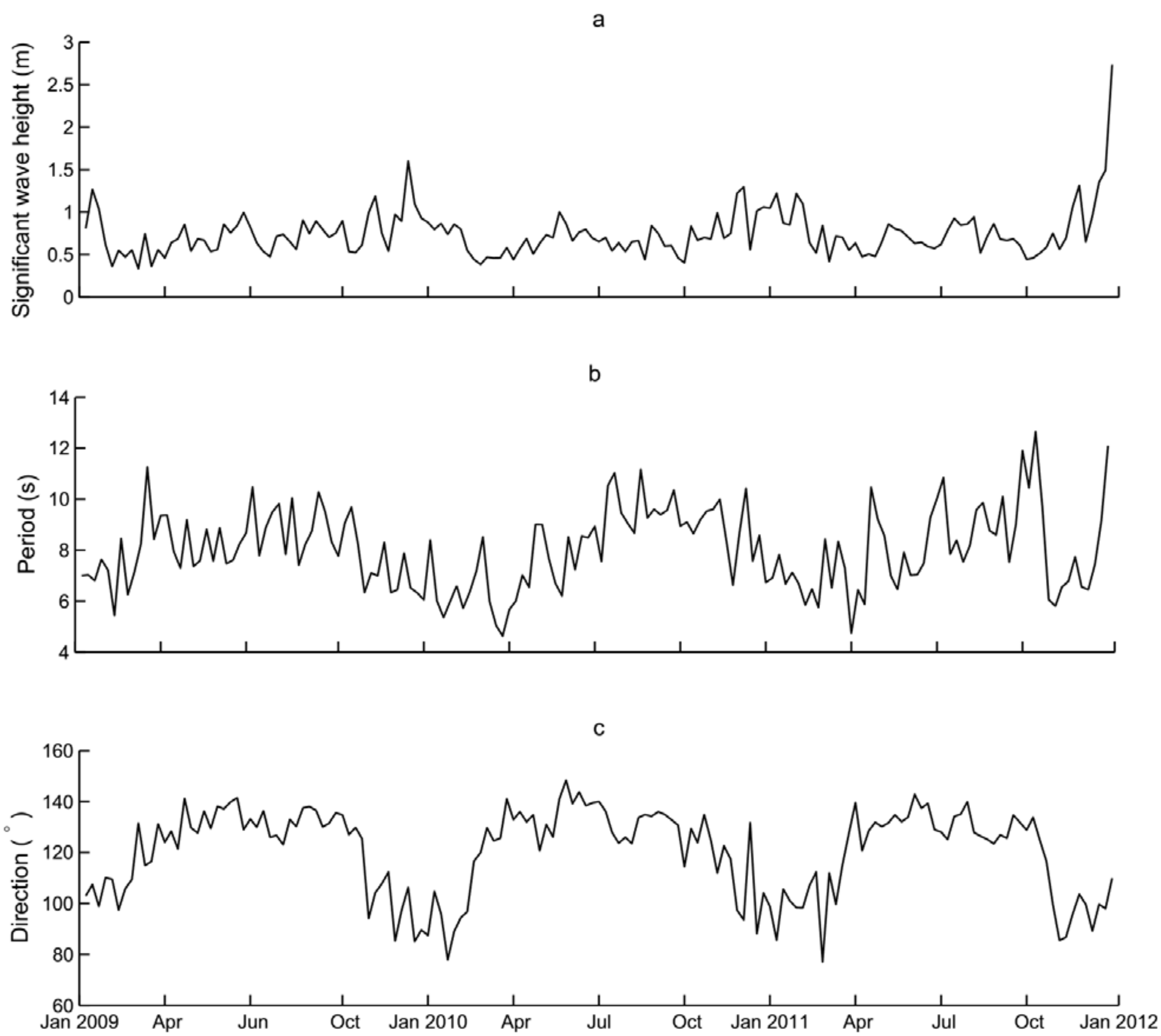

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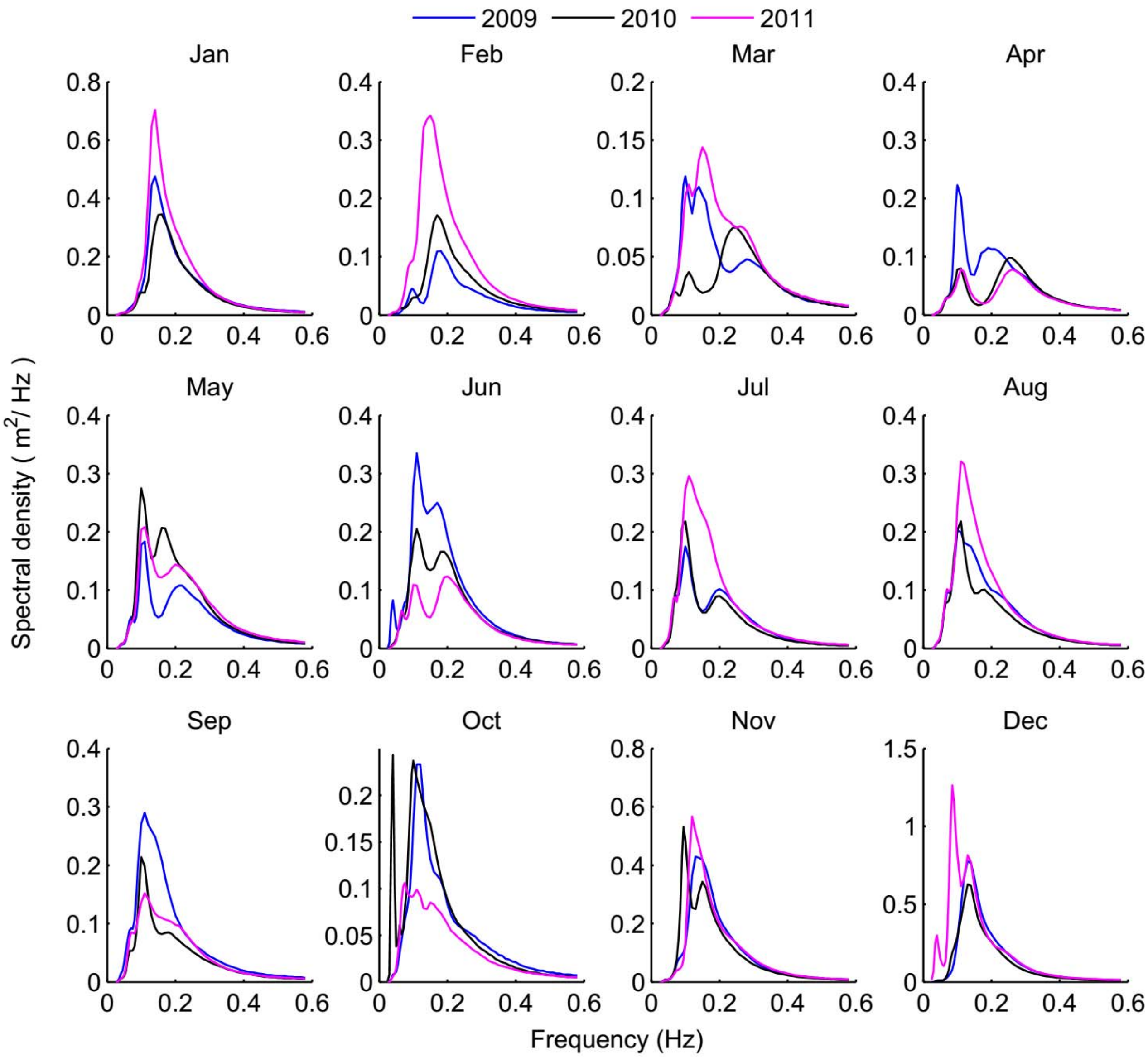

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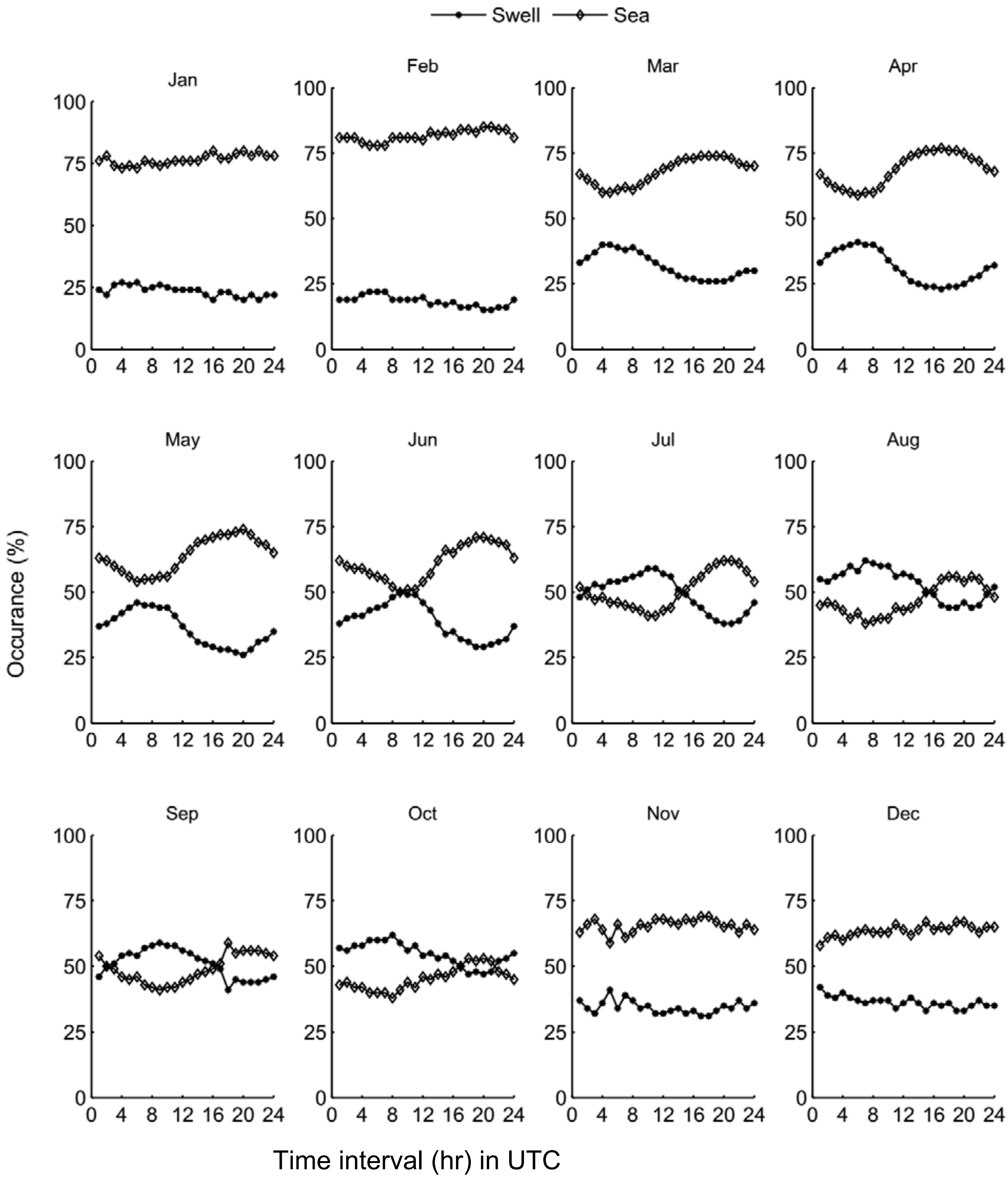

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