

Spatial and temporal variation of surface waves in shallow waters along the eastern Arabian Sea

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Abstract

We studied the spatial and temporal variation of surface waves along eastern Arabian Sea during 2011 and 2012. Measured directional wave data at 2 shallow water locations and the re-analysis datasets (ERA-Interim) at 0.75° intervals at 4 locations were used for the study. The study region covers 270 km along the west coast of India and lies between Karwar and Ratnagiri. Temporal variations of wave parameters were less than 10% at both locations for temporal interval up to 12 h except during the monsoon/storm period. During the storm period, variation in significant wave height within 3 h was around 13% and was up to 26% inside 12 h. Comparatively low (<10 %) spatial variation was found for wave height during the monsoon season and higher variation (>20 %) was observed during non-monsoon season. Pattern of spatial variation of wave parameters were similar during both years for measured and re-analysis datasets. The study shows that during the monsoon period, the wave characteristics were similar for the 270 km long stretch since the waves along this part were predominantly (~72%) swells.

Key Words: Significant wave height, wave period, wave direction, wave spectral energy, west coast of India

1. Introduction

Engineers involved in the planning and design of marine structures require information on waves at a specific location. To derive the wave climate at a location or region, time series wave data covering many years are necessary. Wave data at a specific location is obtained through i) wave measurements, or ii) numerical models, or iii) satellites (Cavaleri and Sclavo, 2006). The wave data obtained from numerical models and satellites need to be verified by the measured data. But due to high expense towards the installation and maintenance of wave measuring instrument, in-situ measurements at many locations remain a challenge even today. Also, carrying out wave measurements in the shallow water locations for long-term is a difficult task due to the intense fishing activity in the near-shore area. Entanglement of the fishing vessels/nets with the moored buoy results in damage to the buoy and the moorings. Similarly, the coastal domain represents a challenging target for exploiting satellite information, where accuracy is degraded due to a number of factors including issues of land contamination in the altimeter and radiometer footprints (Andersen and Scharroo, 2011). In the absence of measured data for a specific location, numerical models are calibrated with the data available for the nearest location and hence it is important to know the spatial variation of wave parameters. The re-analysis datasets and the satellite data have limitations in temporal and spatial resolutions. Hence, it is necessary to understand the variation of each parameter with respect to time and location.

The present study is focused on the eastern Arabian Sea, mainly from Karwar to Ratnagiri (Fig. 1). The waters off the west coast of India are exposed to seasonally reversing winds, with winds from the south-west (SW) during the SW/summer monsoon (hereafter monsoon) period (June to September) and from the north-east (NE) during the post-monsoon period (October to January). The period between NE and SW monsoon is the pre-monsoon period or the fair weather (FW) period. The seasonal changes in winds produce similar changes in the surface waves and hence it is important to know the variations in wave parameters seasonally and inter-annually. Kumar et al. (2012) reported that the seasonal average wave height and period did not vary significantly between three stations covering 200 km along the Karnataka coast, India. Glejin et al. (2012) compared the wave parameters at 3 locations along the eastern Arabian Sea during June to August 2010 covering the monsoon period and found that the wave height increase from the south to north. Since the study of Kumar et al. (2012) covered only the data for one month each representing the 3 seasons and that by Glejin et al. (2012) covered only the monsoon period, we have done a fresh study covering larger spatial interval with continuous data covering 2 years

period. The objective of the study was to know the spatial and temporal variation in surface wave parameters between two locations spaced at 270 km along the eastern Arabian Sea. The variations in surface waves in the near-shore waters were studied with the data obtained from simultaneous measurements carried out at 2 locations using moored directional wave rider buoys and that for the offshore waters were done with the ERA-Interim dataset.

The locations selected for the study were i) off Karwar (southern location) at 15 m water depth (geographic position 14.8217° N, 74.0524° E) and ii) off Ratnagiri (northern location) at 13 m water depth (geographic position 16.9801° N; 73.2584° E). Distance of the locations from the west coast of Indian mainland is 5 km at Karwar and 2 km at Ratnagiri. Distance between Karwar and Ratnagiri is around 270 km and these locations are exposed to deep-water swell waves from the south Indian Ocean. Tides in the study region are mixed and are predominantly semi-diurnal and the average tidal range at Karwar is 1.58 m during spring tide and 0.72 m during neap tide. At Ratnagiri, the average spring tidal range is about 1.8 m and the neap tidal range is 0.9 m (Glejin et al., 2013).

2. Data and methodology

Waves were measured using the Datawell directional wave rider buoy (Barstow and Kollstad, 1991) for a period of 2 years during 1 January 2011 to 31 December 2012. Measurements were made in Coordinated Universal Time (UTC) and the time referred in the paper is UTC. The data recorded continuously at 1.28 Hz and the data for every 30 minutes were processed as one record. The collected time series was subjected to standard error checks for spikes, steepness and constant signals (Haver, 1980) and a total 17418 number of records measured simultaneously at both locations during 2011 and 17416 records during 2012 were used for further analysis. Zero-crossing analysis of the surface elevation time series was used to estimate maximum wave height (H_{max}) and the wave period corresponding to maximum wave height (T_{Hmax}). Fast Fourier Transform of 8 series, each consisting of 256 measured vertical elevations of the buoy data, were added to obtain the wave spectrum. High frequency cut off is set at 0.58 Hz and the resolution is 0.005 Hz. Significant wave height (H_s) which equals $4\sqrt{m_0}$ and the mean wave period (T_z) which equals $2\pi\sqrt{m_0/m_2}$ were obtained from the spectral moment. Where m_n is the n^{th} order spectral moment and is given by $m_n = \int_0^\infty f^n S(f)df$, $S(f)$ is the spectral energy density at frequency f . Peak wave period (T_p) was estimated at the spectral peak. Mean

wave direction (D_p) and directional width (B_M) at spectral peak was estimated as per Kuik et al. (1988). Wind-sea and swell from the measured data was separated through the method described by Portilla et al. (2009). Monthly mean of each parameters based on different temporal intervals ($\frac{1}{2}$, 1, 3, 6, 12 and 24 h) was estimated. Data at half an hour interval was used as a reference data and percentage difference (PD) of each monthly mean data for different intervals from its half hour interval was calculated as;

$PD = ((X-Y)/Y) 100$, where X is the data at 1, 3, 6, 12 and 24 h interval and Y is the data at $\frac{1}{2}$ h interval.

For studying the spatial variation of wave parameters, the data at the southern location (Karwar) was taken as the reference data and the PD for the northern location (Ratnagiri) was calculated. Since the wave climate in the eastern AS shows seasonal variability, while studying the spatial variation of wave parameters between Karwar and Ratnagiri, we used weekly average data instead of monthly/seasonal average.

The re-analysis wave datasets (ERA-Interim) used in this study was from the ECMWF (European Centre for Medium-range Weather Forecast) re-analysis models (see <http://www.ecmwf.int/research/era/do/get/index>). ERA-Interim is the most recent re-analysis provided by ECMWF (Simmons et al., 2007). ERA-Interim is the first re-analysis using adaptive and fully automated bias corrections of satellite radiance observations (Dee and Uppala, 2008). Significant wave height (H_s) data is available at $0.75^\circ \times 0.75^\circ$ grid points and the data for the years 2011 and 2012 for four locations (14.25° N, 73.5° E; 15° N, 72.75° E; 15.75° N, 72.75° E; 16.5° N, 72.75° E) covering Karwar to Ratnagiri were used in the study. These datasets have a temporal interval of 6 h. The southern location (14.25° N, 73.5° E) was taken as reference for studying the spatial variation of H_s .

3. Results and discussions

3.1. Temporal variation

Temporal variation of monthly average wave parameters (H_s , H_{max} , T_z , T_p and D_p) show that the PD of all parameters except T_z was less than 10% (Figs. 2 and 3) for temporal interval up to 24 h. For temporal interval up to 12 h, the PD for all parameters except T_z was in the range of 0 to 3% during most of the time. At Ratnagiri, T_p shows higher PD value (10-15%) during January 2011 and November 2012 and except these months PD value of T_p was less than 10% similar to other wave parameters. The higher

PD value of T_p during these months was due to the presence of swells coming from northwest (NW) and SW direction (Figs. 4a to 4d). The NW swells were more at Ratnagiri than at Karwar and during the monsoon season the NW swells were absent at both the locations (Figs. 4e to 4f). Compared to other parameters, the temporal variation of D_p was very small (<4%) for both locations. The variation of PD of H_s at both locations during both years depend on the seasons since the wave climate of the eastern Arabian Sea is influenced by the monsoonal winds during the SW monsoon resulting in high wave activity (Kumar et al., 2006; Kumar et al., 2010; Glejin et al., 2013). PD of H_s was comparatively low during the SW monsoon period when the wave heights were high and the PD was high during pre-monsoon period when the influence of sea breeze was high. The sea breeze has high impact along the west coast of India during pre-monsoon season (Neetu et al., 2006; Glejin et al., 2013) and the horizontal extent of the sea/land breeze circulation over the Arabian Sea was observed up to 80-100 km (Subrahamanyam et al., 2001). In the present case the measurement locations were within 5 km from the coast and hence the sea/land breeze influenced the wave parameters and resulted in comparatively higher PD of H_s during the pre-monsoon season. In post-monsoon season, the impact of land/sea breeze was comparatively lower than that observed in the pre-monsoon season (Glejin et al., 2013). The influence of land/sea breeze on the wave was negligible during the monsoon seasons since the land/sea breeze system was weak during monsoon system and was mainly during the break-in the monsoon (Mandal, 1992). The study shows that the influence of sea/land breeze was higher on the temporal variation of wave parameters.

Present study indicates that the variation in monthly average value of H_{max} and H_s for data based on different recording intervals was negligible (< 10 %). Glejin et al. (2012) found that during the monsoon season there was no change in the average value of H_s and H_{max} for the data based on different recording intervals of 3, 6, 12 and 24 h.

Monthly maximum value of H_s for different temporal interval is presented in Table 1. Variation in monthly maximum value of H_s was less than 6% for temporal interval up to 3 h except during the storm period in November 2011 (deep depression in eastern Arabian Sea during 26 November to 1 December 2011; IMD, 2011) at Karwar and monsoon period at Ratnagiri. During the storm/monsoon period, variation in H_s was around 15% within 3 h and it was 26% for 12 h. Variation in maximum H_s for temporal interval of 24 h was up to 40% in October at Ratnagiri (Table 1). The study indicates that

data at temporal interval of more than 6 h will miss the monthly maximum H_s values during the SW monsoon and storm period.

The revisiting rate of polar orbiting satellites are 1 or more days hence these satellites do not adequately resolve the short-term event and process characteristics of coastal environment (Brown et al., 2005). With the availability of more than 2 altimeters, for many locations, data should be available for high frequent time interval. To know the chance of missing of H_s event between the revisiting intervals of these satellites here we compared the maximum value of H_s during half, 24 and 48 h temporal intervals (Fig. 5). The maximum PD between the 24 h and 48 h interval datasets were up to 40%. During the monsoon season, the maximum PD for 48 h and 24 h interval data were within the range of 16 to 26%. Also, during the storm event at Karwar, high PD (~26%) was observed. Compared to post-monsoon season, the pre-monsoon season shows high PD in H_s due to the effect of land sea breeze system. From the Figure 5, we can see that during the monsoon season, the missing of higher wave height was larger than that during pre- and post-monsoon season. The average of the difference between maximum H_s with half and 12 h intervals was 0.17 m and that between half and 24 h was 0.25 m. The maximum difference in H_s with $\frac{1}{2}$ h and 24 h interval data was 0.8 m and that with 48 h was 1.4 m. From this we can see that measurement of wave parameters in one location using one satellite with temporal interval of 2 days is insufficient. Multiple observations are needed for better observation of wave parameters, if not it may cause missing of high and short-term wave events generated by oceanographic/meteorological factors. Correction factor was estimated to minimize the error between the data with different temporal intervals. The correction factor for Karwar was 19% and 23.5% for 24 h and 48 h data and that for Ratnagiri was 14% and 29% respectively. Goda (1988) observed that wave data with recording intervals of 6 or 12 h tend to miss the peaks of some storm events and can lead to underestimation of severe wave conditions. In order to compensate for this effect, Allen and Callaghan (1999) used a simple block adjustment factor of 7% for the 6 h recording interval data and 10% for the 12 h recording intervals to each peak H_s value.

Yearly maximum PD value for other wave parameters are shown in Table 2. The PD variation of these parameters also depends upon the seasons. Variation of directional width with time was higher (10-12%) at Ratnagiri and lower (5-8%) at Karwar. The parameters E_{max} , Swell (%), H_{sw} , T_{Hmax} , T_{zw} show generally higher PD (> 10%) than other parameters. The PD of swell percentage shows comparatively low value during monsoon season and that of E_{max} shows this trend in both monsoon and

post-monsoon season since the waves were swell dominated in monsoon and post-monsoon season (Kumar et al., 2012; Sajiv et al., 2012).

3.2 Spatial variation

Spatial variation of wave parameters was studied using measured data and the significant wave height (H_s) from ERA-Interim. Comparison based on buoy data (Fig. 6) indicates that the spatial variation of most of the parameters during pre-monsoon season was comparatively higher than that observed during the post-monsoon season. Variation of H_s observed between the locations was equal to or slightly greater than 20% during pre- and post-monsoon season, where as it was less than 10% during the monsoon season. Similar trend was observed in the case of H_{max} as well. Decreasing of PD of all wave parameters during monsoon season was due to the similar wave condition in the eastern Arabian Sea due to the influence of SW monsoon. Large variation in the wave climate was unlikely along the eastern Arabian Sea since substantial part of the wave energy along this was due to the swells (Kumar et al., 2000; Glejin et al., 2012; Sajiv et al., 2012; Glejin et al., 2013). However, as the waves propagate from deep to shallow water they undergo transformation through their interaction with seabed and the wave characteristics will vary with change in water depth.

The PD of E_{max} was higher among all other parameters during post- and pre-monsoon seasons since single-peaked spectra was large (63%) in the southern location resulting in high E_{max} values compared to the northern location (46%) because of variation in local winds (Kumar et al., 2014). Also the maximum spectral energy density during monsoon was much higher (up to $35 \text{ m}^2 / \text{Hz}$) than that ($< 5 \text{ m}^2 / \text{Hz}$) during the remaining periods (Kumar et al., 2012). PD of T_{Hmax} has higher value in pre-monsoon season than that in the post-monsoon season. For D_p , the higher PD was observed in April and May during both years since during these months the influence of land/sea breeze system was active and at Ratnagiri NW waves were observed whereas at Honnavar (80 km south of Karwar), swells from SW were predominant (Kumar et al., 2014).

Presence of a strong seasonal variation in the wave heights in the eastern Arabian Sea is a well-known feature due to the similar variation in the wind speed (Kumar et al., 2012; Glejin et al., 2013). The monthly mean H_s vary at Karwar from about 0.56 m during December to about 2.30 m in July (Fig. 7). The variation of monthly mean H_s at northern location, 0.54 m in December to 2.36 m in July, almost follows with that of the southern location. In post-monsoon and pre-monsoon seasons, the value of H_s

was low at Karwar than that observed at Ratnagiri. The seasonal variation in H_{\max} was also similar to that of H_s at both locations.

In case of T_p , there was an abnormally higher PD observed in the pre-monsoon season. Kumar et al. (2014) observed that the double-peaked spectra were mostly swell dominated in the southern location of the eastern Arabian Sea and at the northern location during December-May; the spectra were wind-sea dominated due to the strong local winds blowing from northwest. Hence, higher PD was observed for T_p in the pre-monsoon season (Fig. 6). Also, due to the variation in the swell/sea domination at the locations studied, large variation was found in the monthly average value of T_p at both locations during December-May (Fig. 7). At Ratnagiri, the percentage of swells were 26, 71 and 40 during the pre-monsoon, monsoon and post-monsoon period. At Karwar, the percentage of swells were 41, 73 and 53 during the pre-monsoon, monsoon and post-monsoon period. The variation in swell percentage between the two locations was high during pre- and post-monsoon (Figs. 6 and 7) due to the larger presence of swells at Karwar than at Ratnagiri. During the monsoon period, the average value of T_p (~ 11 s) and the percentage of swells was the same at both locations.

It was found that along the study area, PD of H_s based on ERA-Interim dataset increase with increase in latitudes (Fig. 8). For location at 0.75° from the reference location, PD was less than 10% in all seasons. In the case of location at 1.5° away from the reference location, PD was less than 20% in most of the time during post- and pre-monsoon seasons. For this location during monsoon season, PD was less than 10%. PD was greater than 20% during pre-monsoon and post-monsoon season at the location 2.25° away from reference location and was less than 20% during monsoon season.

4. Conclusion

The study results indicate that all parameters which describe the wave characteristics highly depend upon the seasons. Variation in monthly average value of H_{\max} and H_s for data based on different recording intervals was less than 10%. In October, the variation in maximum H_s for temporal interval of 24 h compared to $\frac{1}{2}$ h interval was up to 40%. In the case of re-analysis data, the local influence on significant wave height was negligible than that in the case of buoy data. Hence, the re-analysis data show the latitudinal variation of wave parameters more clearly. For the study locations, high H_s and wave energy was observed during the monsoon season. Most of the wave parameters show low spatial and temporal variation during the monsoon season and same trend was observed in the case of buoy data

and re-analysis data. During the non-monsoon period, higher difference in swell percentage was observed between the locations. The spatial variation of wave parameters between Karwar and Ratnagiri, west coast of India during monsoon season was very low ($< 10\%$ for H_s and H_{max}).

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Annexure: Notations used

B_m = Directional spread

D_p = wave direction corresponding to spectral peak

D_{ps} = peak direction of swell

D_{pw} = peak direction of wind-sea

E_{max} = maximum spectral energy density

ECMWF = European Centre for Medium-range Weather Forecast

ERA = ECMWF Re-Analysis

H_{max} = maximum wave height

H_s = significant wave height

H_{ss} = significant height of swell

H_{sw} = significant height of wind-sea

PD = percentage difference

Swell (%) = Swell percentage

T_{Hmax} = maximum wave period

T_p = Peak wave period

T_z = mean wave period

T_{zs} = mean period of swell.

T_{zw} = mean period of wind-sea.

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Figure Captions

Figure 1. Study locations in the eastern Arabian Sea. Red marks show the ERA-Interim locations

Figure 2. Percentage difference of monthly average wave parameters with different temporal intervals at Karwar during 2011 and 2012

Figure 3. Percentage difference of monthly average wave parameters with different temporal intervals at Ratnagiri during 2011 and 2012

Figure 4. Time series plot of peak wave period and mean wave direction during a) January 2011 at Ratnagiri b) January 2011 at Karwar, c) November 2012 at Ratnagiri, d) November 2012 at Karwar, e) August 2012 at Ratnagiri and f) June 2011 at Karwar

Figure 5. Maximum value of significant wave height observed in temporal intervals of half, 24 and 48 h

Figure 6. Spatial variation of weekly average wave parameters at Ratnagiri with respect to Karwar in 2011 and 2012 based on measured data. Week 5 to 21 is pre-monsoon, 22 to 40 is monsoon and 41 to 52 and 1 to 4 is post-monsoon period.

Figure 7. Spatial variation of monthly average value of wave parameters at Ratnagiri and Karwar in 2011 and 2012

Figure 8. Spatial variation of significant wave height in different ERA-Interim grid points with respect to the southern location (14.25° N; 73.5° E)

Table 1. Monthly maximum values of significant wave height in different temporal intervals

| Location | Interval (h) | Month | | | | | | | | | | | |
|---------------------|-----------------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Karwar (2011) | ½ | 0.9 | 1.3 | 1.2 | 1.1 | 1.4 | 3.2 | 4.1 | 3.2 | 3.6 | 1.2 | 2.3 | 0.9 |
| | 1 | 0.9 | 1.3 | 1.2 | 1.1 | 1.4 | 3.1 | 4.0 | 3.2 | 3.6 | 1.2 | 2.2 | 0.8 |
| | 3 | 0.9 | 1.2 | 1.2 | 1.1 | 1.4 | 3.1 | 4.0 | 3.2 | 3.4 | 1.2 | 2.0 | 0.8 |
| | 6 | 0.9 | 1.2 | 1.2 | 1.0 | 1.4 | 3.1 | 3.8 | 3.0 | 3.4 | 1.2 | 2.0 | 0.8 |
| | 12 | 0.9 | 1.2 | 1.2 | 1.0 | 1.3 | 3.0 | 3.6 | 3.0 | 3.4 | 1.0 | 1.7 | 0.8 |
| | 24 | 0.8 | 1.2 | 1.2 | 1.0 | 1.3 | 3.0 | 3.3 | 3.0 | 3.4 | 1.0 | 1.7 | 0.7 |
| Ratnagiri (2011) | ½ | 1.0 | 1.8 | 1.2 | 1.2 | 1.6 | 3.2 | 3.9 | 3.1 | 4.2 | 0.9 | 1.2 | 0.9 |
| | 1 | 1.0 | 1.7 | 1.2 | 1.2 | 1.6 | 3.2 | 3.8 | 3.0 | 4.2 | 0.9 | 1.2 | 0.9 |
| | 3 | 1.0 | 1.5 | 1.1 | 1.1 | 1.5 | 3.1 | 3.8 | 2.9 | 3.6 | 0.9 | 1.2 | 0.8 |
| | 6 | 1.0 | 1.5 | 1.1 | 1.1 | 1.5 | 3.1 | 3.8 | 2.9 | 3.6 | 0.9 | 1.2 | 0.8 |
| | 12 | 0.9 | 1.5 | 1.1 | 1.1 | 1.4 | 3.1 | 3.4 | 2.9 | 3.6 | 0.9 | 1.2 | 0.8 |
| | 24 | 0.8 | 1.5 | 1.1 | 1.1 | 1.4 | 3.0 | 3.4 | 2.9 | 3.2 | 0.9 | 1.2 | 0.8 |
| Karwar (2012) | ½ | 1.2 | 1.6 | 1.3 | 1.5 | 1.3 | 3.3 | 3.6 | 3.0 | 2.7 | 1.3 | 0.8 | 0.9 |
| | 1 | 1.2 | 1.6 | 1.3 | 1.5 | 1.3 | 3.3 | 3.6 | 3.0 | 2.7 | 1.3 | 0.8 | 0.9 |
| | 3 | 1.2 | 1.5 | 1.3 | 1.5 | 1.3 | 3.3 | 3.6 | 3.0 | 2.7 | 1.3 | 0.8 | 0.9 |
| | 6 | 1.1 | 1.5 | 1.3 | 1.4 | 1.3 | 3.3 | 3.3 | 2.8 | 2.5 | 1.3 | 0.8 | 0.9 |
| | 12 | 1.0 | 1.5 | 1.3 | 1.4 | 1.3 | 3.0 | 3.3 | 2.8 | 2.5 | 1.3 | 0.8 | 0.9 |
| | 24 | 1.0 | 1.5 | 1.1 | 1.4 | 1.2 | 3.0 | 3.3 | 2.5 | 2.5 | 1.2 | 0.7 | 0.8 |
| Ratnagiri (2012) | ½ | 1.5 | 2.1 | 1.3 | 1.6 | 1.3 | 3.4 | 3.5 | 2.8 | 2.5 | 1.5 | 0.9 | 0.9 |
| | 1 | 1.5 | 2.0 | 1.3 | 1.6 | 1.3 | 3.4 | 3.4 | 2.8 | 2.5 | 1.5 | 0.9 | 0.9 |
| | 3 | 1.5 | 2.0 | 1.3 | 1.5 | 1.3 | 2.9 | 3.4 | 2.8 | 2.5 | 1.4 | 0.9 | 0.9 |
| | 6 | 1.4 | 1.8 | 1.2 | 1.4 | 1.3 | 2.9 | 3.4 | 2.8 | 2.5 | 1.4 | 0.9 | 0.9 |
| | 12 | 1.4 | 1.6 | 1.2 | 1.4 | 1.3 | 2.8 | 3.3 | 2.8 | 2.2 | 1.4 | 0.9 | 0.9 |
| | 24 | 1.4 | 1.6 | 1.2 | 1.4 | 1.3 | 2.7 | 3.3 | 2.8 | 2.2 | 0.9 | 0.9 | 0.9 |

Table 2. Maximum value of percentage difference of monthly average wave parameters during temporal intervals from half to 24 h at Karwar and Ratnagiri during 2011 and 2012

| Parameter | 2011 | | 2012 | |
|----------------------------------------------------------------|--------|-----------|--------|-----------|
| | Karwar | Ratnagiri | Karwar | Ratnagiri |
| Significant wave height of swell (H_{ss}) | 8.2 | 6.9 | 3.3 | 8.3 |
| Significant wave height of wind sea (H_{sw}) | 10.9 | 13.2 | 8.2 | 10.6 |
| Wave period associated with maximum wave height (T_{Hmax}) | 10.9 | 9.9 | 8.9 | 10.0 |
| Mean wave period of swell (T_{zs}) | 6.3 | 5.7 | 1.9 | 7.4 |
| Mean wave period of wind sea (T_{zw}) | 11.1 | 13.9 | 8.9 | 10.4 |
| Swell direction (D_{ps}) | 1.4 | 2.8 | 1.6 | 3.8 |
| Wind sea direction (D_{pw}) | 11.6 | 4.0 | 6.5 | 2.3 |
| Directional width (B_M) | 5.7 | 10.7 | 8.4 | 12.6 |
| Percentage of swell | 9.2 | 15.0 | 7.5 | 11.8 |
| Maximum spectral energy density (E_{max}) | 11.9 | 17.2 | 11.9 | 17.0 |

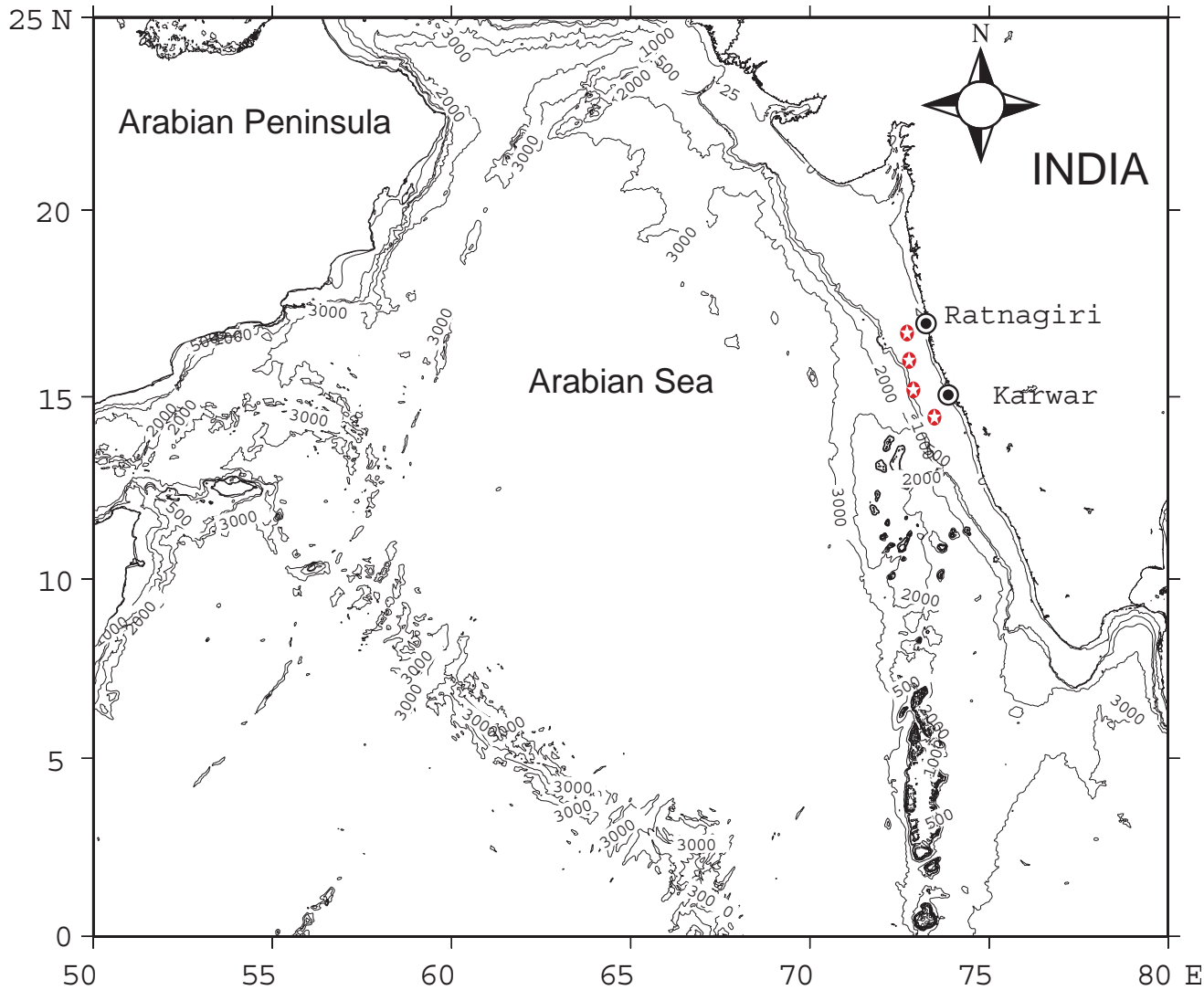


Figure 1. Study locations in the eastern Arabian Sea. Red marks show the ERA-Interim locations

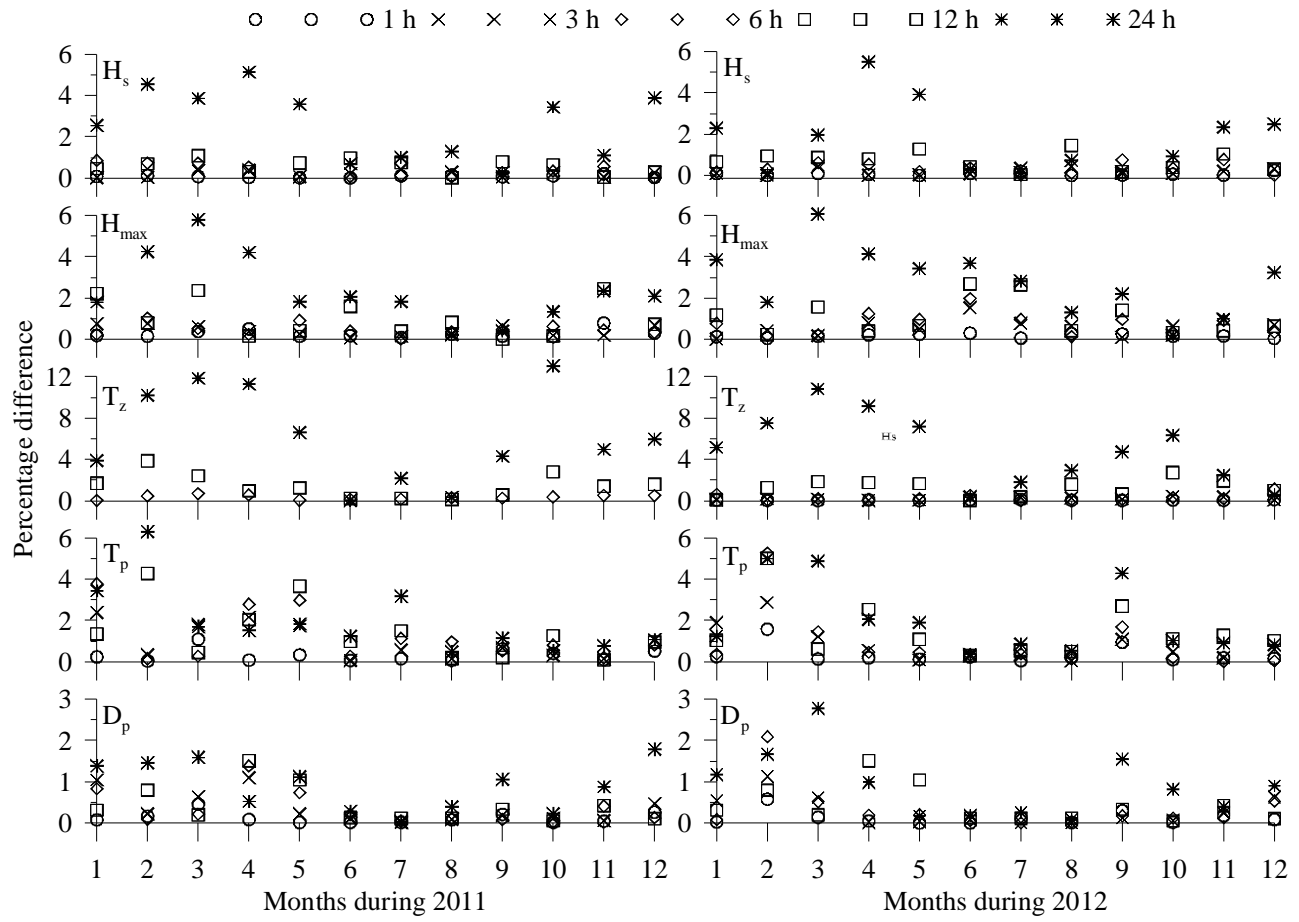


Figure 2. Percentage difference of monthly average wave parameters with different temporal intervals at Karwar during 2011 and 2012

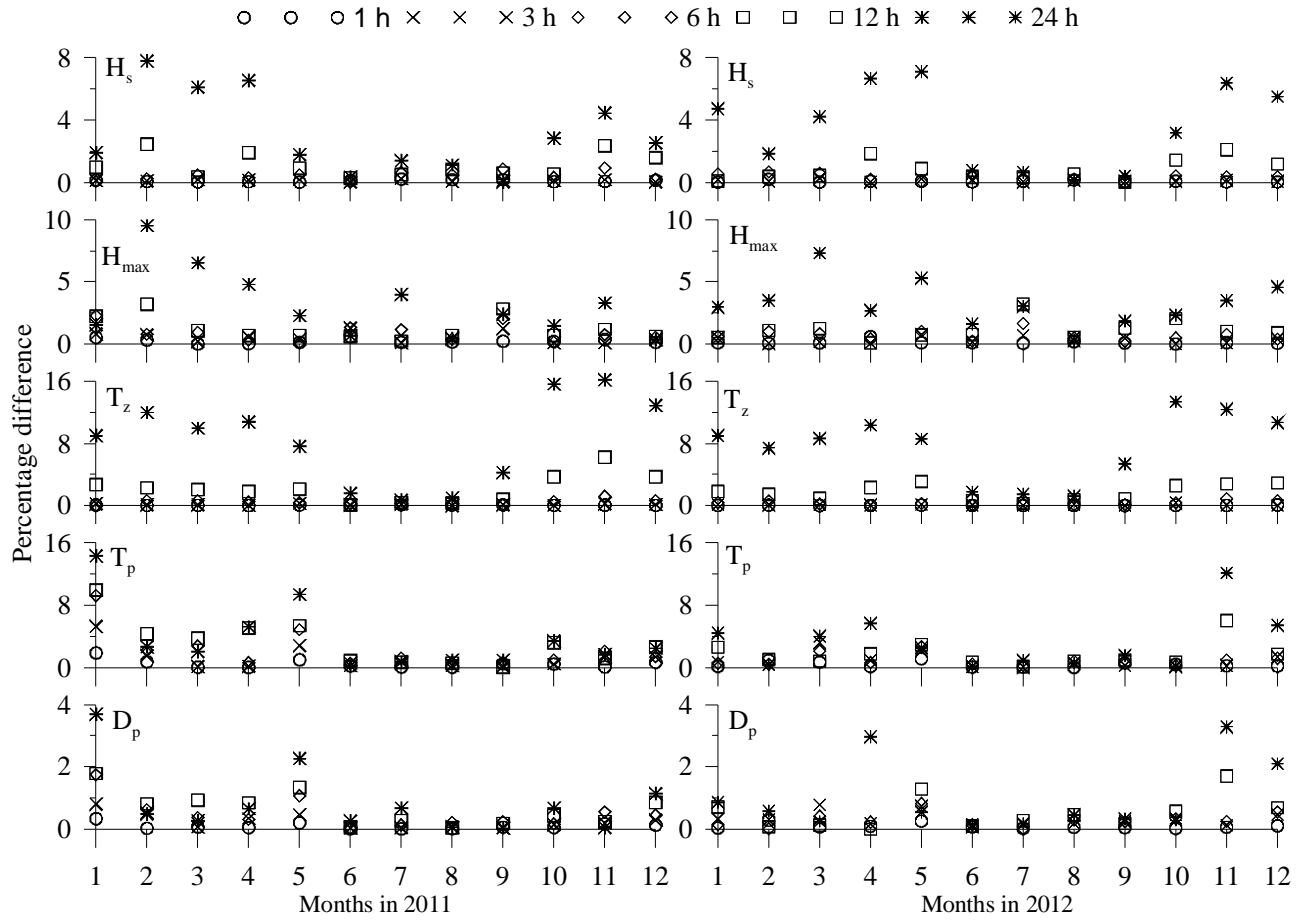


Figure 3. Percentage difference of monthly average wave parameters with different temporal intervals at Ratnagiri during 2011 and 2012

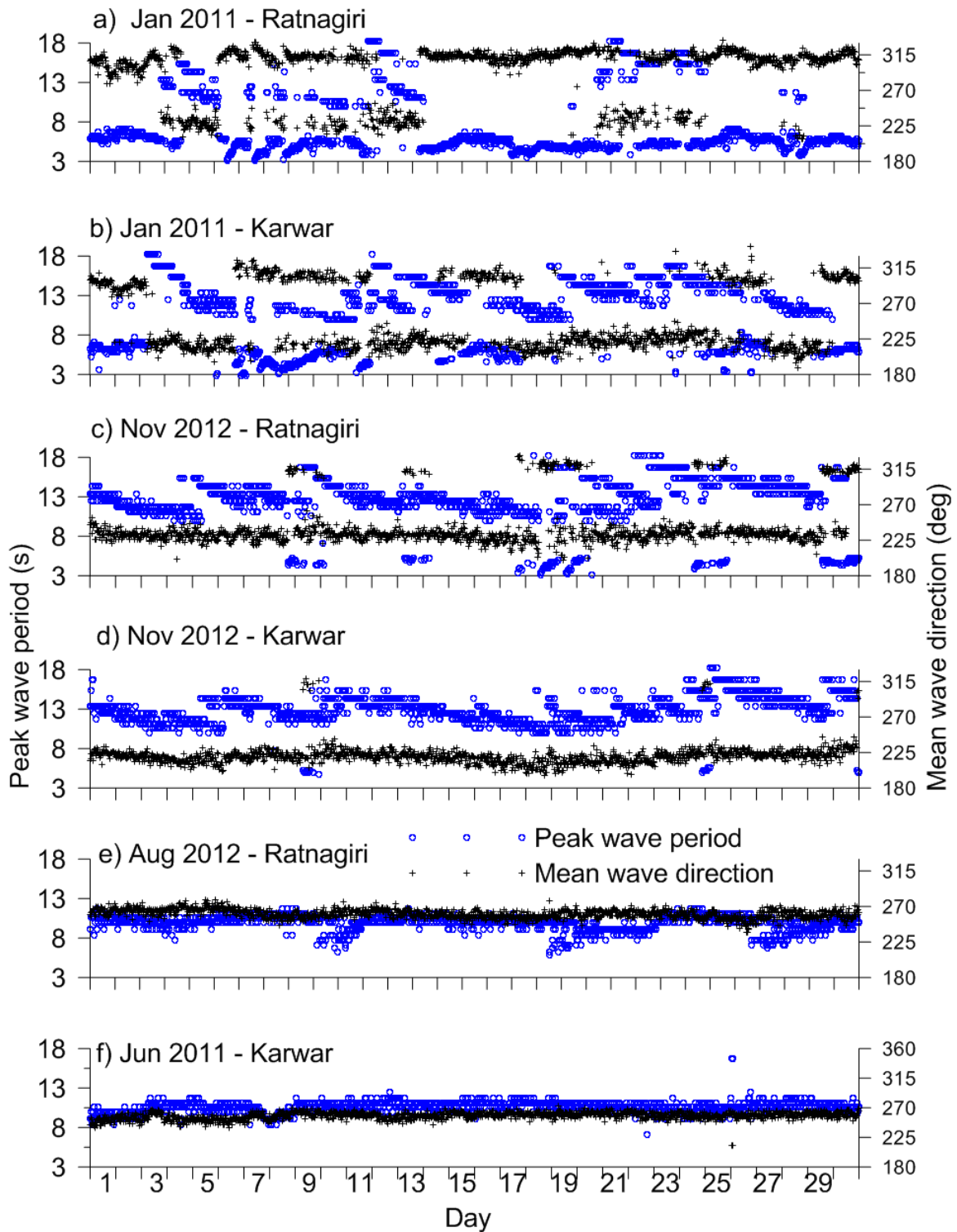


Figure 4. Time series plot of peak wave period and mean wave direction during a) January 2011 at Ratnagiri b) January 2011 at Karwar, c) November 2012 at Ratnagiri, d) November 2012 at Karwar, e) August 2012 at Ratnagiri and f) June 2011 at Karwar

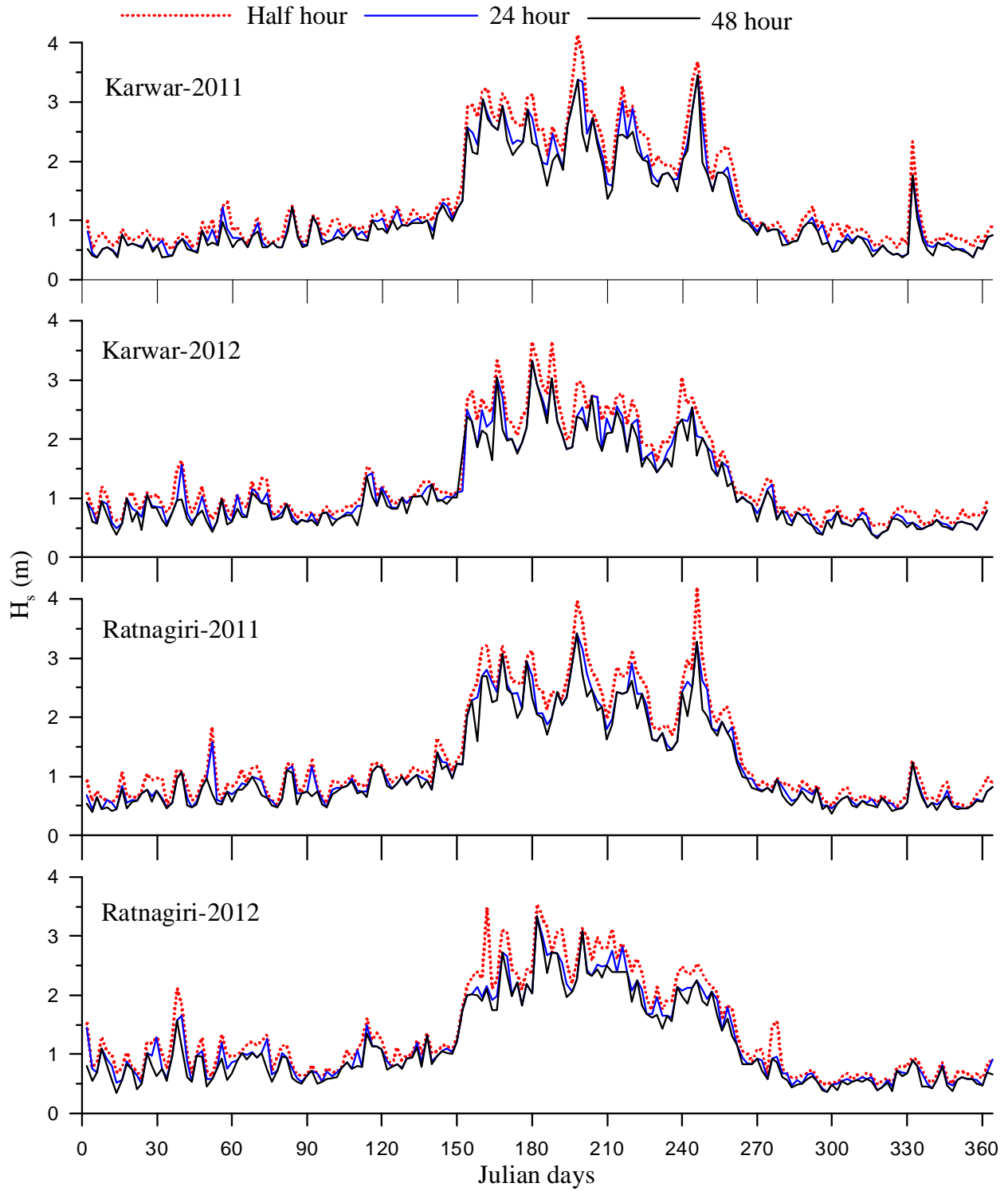


Figure 5. Maximum value of significant wave height observed in temporal intervals of half, 24 and 48 h

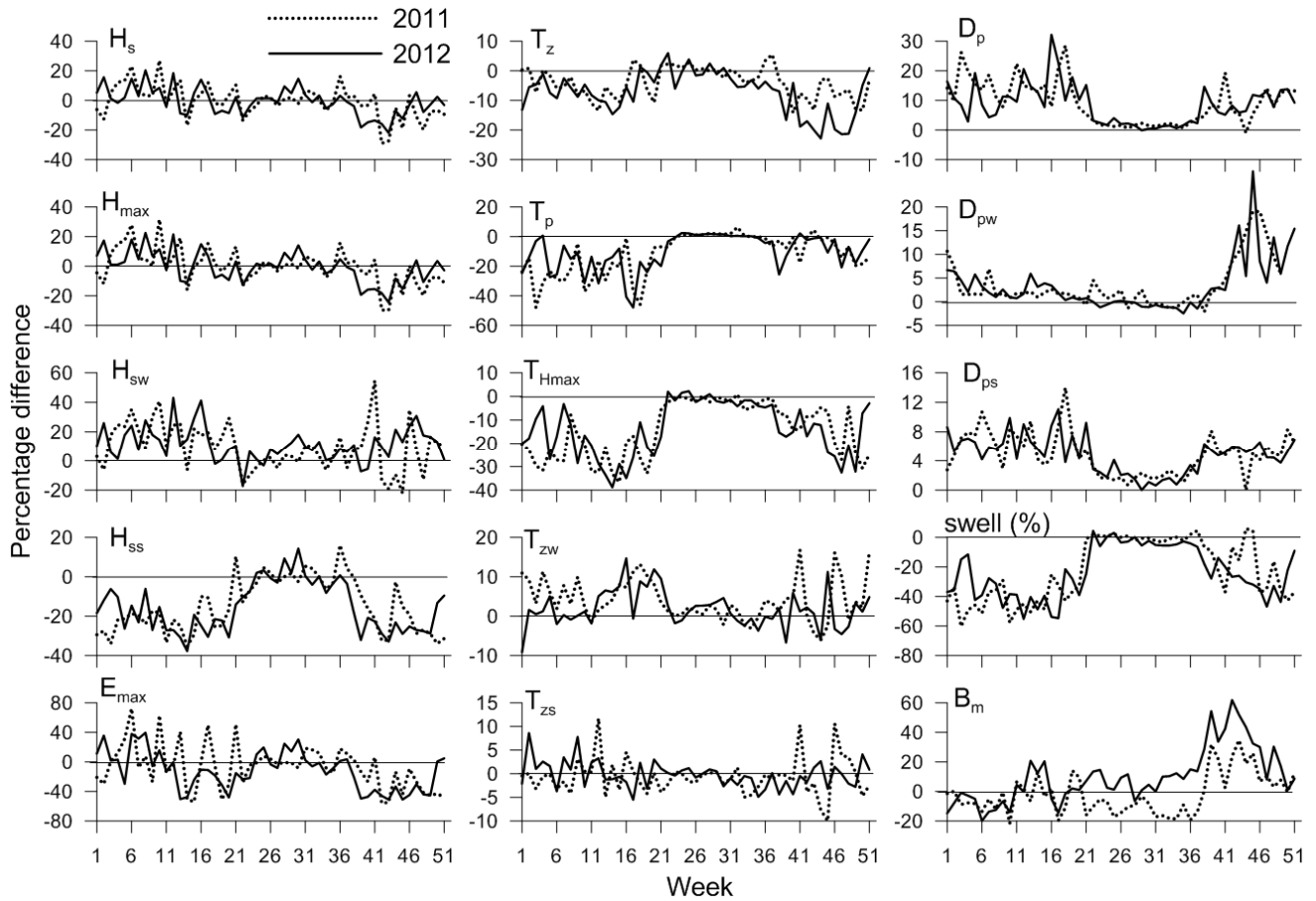


Figure 6. Spatial variation of weekly average wave parameters at Ratnagiri with respect to Karwar in 2011 and 2012 based on measured data. Week 5 to 21 is pre-monsoon, 22 to 40 is monsoon and 41 to 52 and 1 to 4 is post-monsoon period.

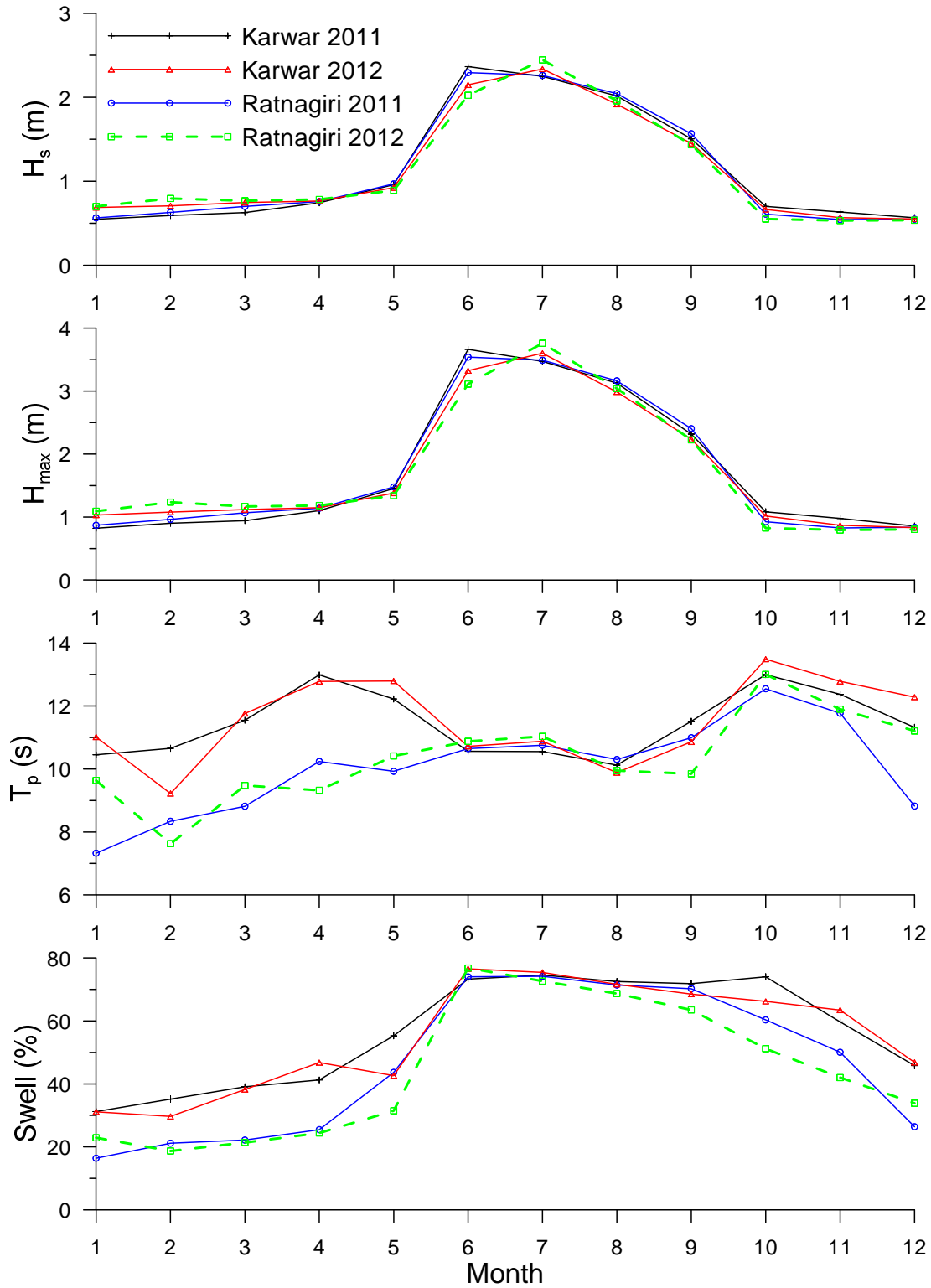


Figure 7. Spatial variation of monthly average value of wave parameters at Ratnagiri and Karwar in 2011 and 2012

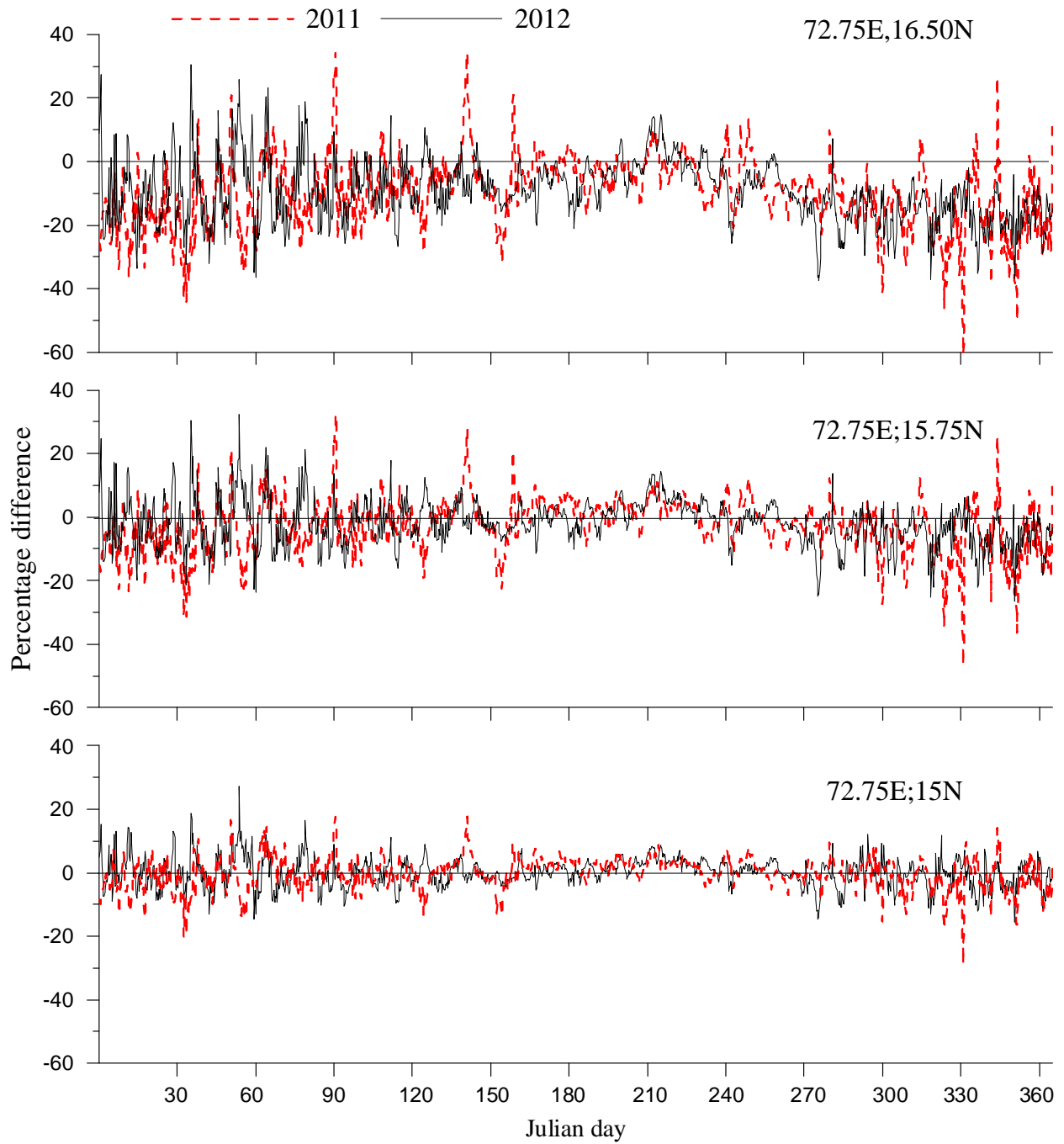


Figure 8. Spatial variation of significant wave height in different ERA-Interim grid points with respect to the southern location (14.25° N;73.5° E)