

## **Spatial and temporal variations of wave height in shelf seas around India**

V. Sanil Kumar, T.R.Anoop

CSIR-National Institute of Oceanography (Council of Scientific & Industrial Research), Dona Paula, Goa 403 004 India

e-mail: sanil@nio.org Tel: 0091 832 2450 327 Fax: 0091 832 2450 602

### **Abstract**

The spatial and temporal variations of wave height in shelf seas around Indian mainland are examined based on the ERA-Interim dataset produced by the European Centre for Medium-Range Weather Forecasts. The study shows that during the summer monsoon, higher wave heights are observed in all locations except at the southern locations in the shelf seas around India, where the winter monsoon is predominant. The annual average significant wave height is highest (~ 1.6 m) at the southern location. During 1979 to 2012, a weak statistically significant increasing trend (maximum ~ 0.20 cm/year) in wave height is observed in the northern and southern region of eastern Arabian Sea, whereas the middle region shows negligible negative trend. A weak decreasing trend (maximum ~ -0.18 cm/year) in wave height is observed in the western Bay of Bengal except along the southern region. At most of the locations weak decreasing trend (0.1 to 2.5 cm/s/year) is observed for the annual mean wind speed. The conflicting trends in the wind speed and wave height are mainly due to the swell dominance in the North Indian Ocean.

**Key Words:** Significant wave height, Climate change, Inter-annual variability, Arabian Sea, Bay of Bengal

## 1. Introduction

The study of long-term trend in wave climate has higher importance since change in wave climate is the good indicator of change in wind pattern, sea surface temperature and pressure pattern. Information of long-term variation and spatial distribution of wave climate is also required to plan marine facilities and marine navigation. In the semi-enclosed basins like Arabian Sea (AS) and Bay of Bengal (BoB), the wave climate is most sensitive to wind pattern (Weisse and Storch 2010). BoB is an area generally prone to cyclone events and these events can cause large inter-annual variations in wave parameters. Generally significant wave height ( $H_s$ ) is used to study the wave climate at a location. Long-term and decadal trend of wave climate in the different parts of major oceans are studied (Carter and Draper 1988; Allan and Komar 2000; Gower 2002; Gulev and Grigorieva, 2004; Young et al. 2011; Appendini et al. 2014). For the seas around India, the long-term trend in wave height is not estimated in the past mainly due to the scarcity of the in situ/model data. Wave statistics based on the ship reported visual data is studied by Sundar (1986) for southeast coast of India based on 10 years data and around the Indian coast based on 19 years data by Chandramohan et al. (1991). Shallow water wave characteristics of west and east coast of Indian subcontinent are studied mainly based on measured data covering one-year period (Nayak et al. 1992; Kumar and Anand, 2004; Glejin et al. 2013a; Gowthaman et al. 2013; Kumar et al. 2014). Inter-annual variations in wave characteristics during 3-yr period at a shallow water location in eastern AS are studied (Sajiv et al. 2012). Recently, the spatial and temporal variation in wind speed and wave height at a location off the west coast of India and in the central BoB during 34-yr is studied by Shanas and Kumar (2014a; 2014b). Bhaskaran et al. (2014) studied the impact of climate change on variability of maximum significant wave height and wind speeds over the Indian Ocean basin based on the daily observation of satellite altimeter for a period of 21 years (1992-2012).

The waters off the North Indian Ocean (NIO) is exposed to seasonally reversing winds, with winds from the southwest (SW) during the summer monsoon period (June to September) and from the northeast (NE) during the winter monsoon period (October to January). The period between the winter and summer monsoon is the fair weather (FW) period. The seasonal changes in winds produce similar changes in the surface waves. Since the spatial and temporal variation in  $H_s$  covering the entire shelf seas around Indian mainland is not studied, a study is carried out. The present analysis is aimed at examining whether there is a linear trend in  $H_s$  over the period 1979 to 2012. The decadal variation in  $H_s$  is also examined.

## 2. Materials and methods

Nineteen locations in the shelf seas of India are selected for the study considering approximately 1.5 ° spacing in latitude of the locations since the study by Kumar et al. (2012) shown that the average wave characteristics do not vary significantly within 200 km distance. Among these 19 locations, 11 locations are in the western side and 8 locations in the eastern side of the Indian mainland (Fig. 1). The locations studied are in water depth more than 50 m (Table 1).

ERA-Interim global atmospheric reanalysis dataset (Dee et al. 2011) produced by the European Centre for Medium Range Weather Forecast (ECMWF) is used in the study. The ERA-Interim data are the latest global oceanic and atmospheric reanalysis data ([http://apps.ecmwf.int/datasets/data/interim\\_full\\_daily/](http://apps.ecmwf.int/datasets/data/interim_full_daily/)) and these data sets are available from 1979 to present. Temporal resolution of the data set is 6 hour interval and it is available in different spatial resolution. We have used significant wave height (Hs) in spatial resolution of 0.75° X 0.75° for the study. ERA-Interim dataset is superior not only on account of its high resolution but also because of its superior data assimilation system. An updated atmospheric model (the Integrated Forecast System Cycle 31r2), which includes increased pressure levels and additional cloud parameters that maximize improved model physics is used in the data generation (Simmons et al. 2007). The incorporated wave model is based on the WAM (global ocean WAVE prediction Model) approach (Komen et al. 1994). Quality control for wave height observation includes a background check (Dee et al. 2011). Shanas and Kumar (2014b) compared the ERA-Interim Hs for the period 2003, 2004 and 2005 with the measured buoy data at the central BoB and reported that the correlation coefficient values for the Hs during 2003 (May-Nov), 2004 (July-Dec) and 2005 (Jan-May) as 0.88, 0.93 and 0.92, respectively. Even though there is a difference in the slope due to the under-prediction of Hs of high waves (Hs > 2.5 m) up to 15%, the mean value of the ERA-Interim Hs is 1.4 m and that measured is 1.5 m. Although the ERA-Interim datasets are validated with the buoy measured data for various regions (Stopa and Cheung 2014), before analysing the trend in wave height in the study area, the ERA-Interim Hs data were compared with the available in-situ measured buoy data.

The measured wave data collected using a moored Seatex buoy (Oceanor, Norway) under the National Data Buoy Programme (Premkumar et al. 2000) at 1 location in the AS during May-December 2005 and 1 location in the BoB during July 2004 to May 2005 are used for comparison with the ERA-Interim Hs data. The heave data of the buoy is recorded at 2 Hz interval for 17 minutes duration and from the recorded heave data, the wave spectrum is obtained through Fast Fourier Transform and the Hs is estimated from the zeroth spectral moment ( $m_0$ ) as  $H_s = 4 \sqrt{m_0}$ .

Comparison of ERA-Interim data with measured data for both locations indicates that ERA-Interim data show good agreement with observation (Fig. 2). The correlation coefficient ( $r$ ) value for the  $H_s$  is 0.96 with bias value of -0.17 m, scatter index (SI) is also small (0.21), but the ERA-Interim data underestimate the  $H_s$  for values more than 3.5 m in AS and 2.5 m in BoB. During the year 2005, the difference between the average value of the  $H_s$  between the measured and ERA-Interim data is less (0.2 m in AS and BoB), whereas the difference between the maximum  $H_s$  value is high (1.5 m in AS and 0.6 m in BoB). Since the wave height in AS is higher than that in BoB, higher root mean square error (RMSE) is found in AS than that of BoB. Wave data in ERA-interim were produced on a grid with resolution of the order of 110 km and the resolution of the model is inadequate to resolve tropical cyclones and hence high waves are underestimated. Since the high wave heights are underestimated, we cannot use the ERA-Interim data for estimating the trend of the annual maximum  $H_s$ .

The trend of  $H_s$  is estimated based on the slope of the linear best-fit curve to the annual mean  $H_s$  for 34 years. The significant trend of the  $H_s$  is estimated by applying Kendall's Tau-Sen test (Sen 1968; Burkey 2006; <http://www.mathworks.com/matlabcentral/fileexchange>).

### **3. Results and discussion**

#### **3.1 Variation in monthly average $H_s$**

##### **3.1.1 Western shelf seas of India**

During the SW monsoon period,  $H_s$  increases from south to north along the western shelf seas with less monthly average  $H_s$  (~2.3 m) in the south (locations 9 to 11). Locations one to seven have higher influence of monsoon swells than other locations and these locations have average  $H_s$  of 3 m during July (Fig. 3). Earlier studies (Kumar et al. 2010) also indicate that locations off the west coast of the India have larger influence of SW monsoon and resulted in maximum  $H_s$  up to 6 m. The present study shows that the maximum  $H_s$  (~6.3 m) are at locations 5 and 6. During the major monsoon months, June and July, at locations 9 to 11, wave height is almost the same. During the FW and winter monsoon seasons wave height in all locations are in the range of 0.6 to 1.5 m. At location ten, there is a decrease in wave height during January to March (~ 1.7 to 1.3 m) and then there is an increase. The locations 8 to 9 are in the shadow region of Lakshadweep Islands and these islands make a barrier for swells reaching to these locations. The Island shadow causes minimum wave height in these locations during monsoon months compared to other locations.

Annual average  $H_s$  is highest (~ 1.6 m) at the southern location 11 since the wave height at this location is relatively high during FW and winter monsoon seasons and at other locations it is 1.3 to

1.4 m (Table 1). The annual average  $H_s$  during 2008 to 2010 at shallow water (water depth  $\sim 10$  m) between locations 6 and 7 based on measured data (Sajiv et al. 2012) is 1 m. Coastal wave heights are a result of modifications due to bathymetry and nearshore currents and hence lower wave height is observed in the shallow water compared to deep water. Except locations 1, 3 to 6, all other locations are at water depth more than 100 m. Since the water depth at the locations studied is more than half the wave length, the influence of seabed on the waves will be negligible.

### **3.1.2 Eastern shelf seas of India**

For locations 12 to 15, along the western BoB, the effect of monsoon is less than that observed at locations 16 to 19 (Fig. 4). Among the eight locations considered in the eastern shelf seas, 2 locations (12 and 13) are in the shadow region of Sri Lankan land mass. Maximum monthly average  $H_s$  observed in western BoB is 2.2 m (location 18) and is less than the maximum monthly average  $H_s$  found in the eastern AS. Effect of SW monsoon on the wave is less in western BoB than in the eastern AS since the AS branch of monsoon is powerful than BoB branch. The wave height during monsoon along the east coast of India increases from south to north. For the southern locations (locations 12 to 14), NE monsoon has equal or greater influence than SW monsoon. Effect of NE monsoon gradually decreases from south to north during the NE monsoon season. Monthly average  $H_s$  along western BoB are almost the same in major monsoon months (June to August).

The annual average  $H_s$  varies from 0.9 to 1.4 m in the eastern shelf seas. The annual average  $H_s$  during 2010 at shallow water between locations 16 and 17 based on measured data is 1 m (Kumar et al. 2013a). The maximum  $H_s$  in the eastern shelf seas is 5.5 and is at locations 17 and 18. Maximum  $H_s$  observed in the eastern shelf seas is less than that observed in the western shelf seas (6.3 m). During 2010, the maximum measured  $H_s$  in shallow water location in eastern shelf seas were 3 m off Visakhapatnam and 2.7 m off Puducherry and 4.2 m off Ratnagiri and 3.7 m off Honnavar in the western shelf seas (Kumar et al. 2013a). The measured data also indicate that the maximum  $H_s$  in the eastern shelf seas are less than that in the western shelf seas except during the tropical cyclone (TC) period. Amrutha et al. (2014) reported maximum  $H_s$  of 7.3 m in the eastern shelf seas of India off Gopalpur during the TC Phailin. The average  $H_s$  during February-October off Gopalpur including the TC Phailin is 1.3 m and the average  $H_s$  excluding the TC is 1.26 m. During the TC Thane maximum  $H_s$  of 6 m is reported off Puducherry, eastern shelf seas of India (Kumar et al. 2013c). The annual  $H_s$  off Puducherry is 0.77 m including the TC Thane and is 0.75 m excluding the TC. Even though large wave heights are generated during the tropical cyclone, the influence of tropical cyclone on the annual average  $H_s$  is not significant since the influence of tropical cyclone is only 3 to 4 days (Amrutha et al., 2014).

### **3.2 Long-term variation in annual average Hs**

Here, in this section we studied the trend in wave climate at selected locations in shelf seas of India from 1979 to 2012.

#### **3.2.1 Western shelf seas of India**

The study shows that long-term trend variation in wave climate is different for different locations (Fig. 5). Based on the trend, we can divide the eastern AS as three regions, northern region of increasing trend (locations 1 to 5) and middle region of decreasing (locations 6 to 8) trend and southern region (locations 9 to 11) of increasing trend. In the northern region, except northernmost location (location 1) all other locations show a decrease in positive trend from north to south, whereas for southern region an increase in positive trend is found from north to south. In location 1, the increasing trend is 0.11 cm/year. Minimum increasing trend observed in western shelf seas is at location 5 (0.01 cm/year) and maximum is observed at location 2 (0.20 cm/year). In the case of decreasing trend, minimum is observed at location 8 (-0.02 cm/year) and maximum is observed at locations 6 and 7 (both have -0.03 cm/year). The trend of Hs at locations 4 to 9 is negligible ( $< 0.05$  cm/year) indicating that the annual average Hs at these locations from 1979 to 2012 is almost the same. The average trend in Hs for all the locations in the western shelf seas is 0.06 cm/year. The estimated trends in the northern locations in the AS (locations 1 to 3) are statistically significant with 90% confidence limit. The estimated trend at other locations is statistically insignificant.

The study using altimeter data for a period of 18 years in the Indian Ocean indicates that the variation in Hs is almost negligible (Kumar et al 2013b). Young et al. (2011) based on the 23 year period (1985-2008) satellite altimeter measurements indicate a weak increase (0-0.25% of annual mean value) of Hs in NIO. So the negligible increase in Hs observed in most of the locations agrees to the observations of Young et al. (2011). Shanas and Kumar (2014a) also observed negligible upward trend (0.012 cm/year) in annual mean Hs for shallow water location in western shelf seas.

In order to know the influence of local winds on the waves, the trend of wind speed at the study locations is examined. In the western shelf seas the annual average wind speed varied from 4.4 to 6.4 m/s (Table 1). Decreasing trend of 0.1 to 1.7 cm/s/year is observed for the annual mean wind speed at all the locations except at the southern most location (Fig. 6). At the southern most location increasing trend (0.9 cm/s/year) is observed. The conflicting trends in the wind speed and wave height are mainly due to the swell dominance in the eastern AS. The earlier studies indicated propagation of swells from the Southern Ocean to NIO (Glejin et al. 2013a). Since the waves in the eastern AS are mainly the swells arriving from Southern Ocean, the increase in Hs is due to the

increase in swells in the Southern Ocean. Increasing trend in Hs is observed for Indian Ocean sector of Southern Ocean (Hemer et al. 2010). Shanas and Kumar (2014a) also observed negligible upward trend (0.012 cm/year) in annual mean Hs for shallow water location in western shelf seas and annual mean wind speed shows a statistically significant decreasing trend of 1.5 cm/s/year. Bhaskaran et al. (2014) reported that the maximum significant wave height and wind speeds over the Southern Ocean increased during 1992-2012 and these swells influenced the waves in certain sectors of the NIO.

### **3.2.2 Eastern shelf seas of India**

The long-term trend of wave climate in western BoB shows another pattern. A decreasing trend for locations 12 (southernmost location) to 16, at location 17 the average Hs is similar for 34 years and an increasing trend is found at locations 18 and 19 (Fig. 7). At locations 12 to 13, 50% of the waves are the locally generated short period waves (Glejin et al. 2013b). Hence the decrease in wave height at this location can be related to the decrease in local wind speed. Shanas and Kumar (2014b) observed statistically declining trends in the mean and extreme wind speed (90<sup>th</sup> percentile) with increasing trend in extreme significant wave height (SWH) in the central BoB. The conflicting trends in the wind and wave height in central BoB is mainly due to the swell dominance at the region. In this shelf sea region, maximum increasing trend is observed at location 19 (0.12 cm/year) and maximum decreasing trend is observed at location 15 (-0.18 cm/year). Apart from location 14, 15, 18 and 19, the increasing/decreasing trend in annual Hs is negligible (<0.05 cm/year). The average trend for all the locations in the eastern shelf seas is -0.02 cm/year and is negligible. The estimated trends at locations 14 and 19 in the BoB are statistically significant with 90% confidence limit and at other locations the estimated trend is statistically insignificant.

In the eastern shelf seas the annual average wind speed varied from 5.2 to 6.1 m/s (Table 1). Decreasing trend (0.2 to 2.5 cm/s/year) of wind speed is observed in the eastern shelf seas except at the northern locations 18 and 19 (Fig. 8). Similar to the western shelf seas conflicting trends in the wind and wave height is observed in the northern BoB and is similar to the observation in the central Bay of Bengal by Shanas and Kumar (2014b). In the eastern shelf seas also swell dominance is observed (Kumar et al., 2014). Nayak et al. (2013) reported that non-linear interaction from distant long period swells generated in the Southern Ocean can modulate the local wind waves in the south-western BoB.

### **3.3 Decadal variation in Hs**

Variation in the Hs in different decades are examined by grouping the decadal period in terms of the 1980s (1980-1989), 1990s (1990-1999) and 2000s (2000-2009). The average values of the Hs and

the maximum Hs during different decades are presented in Figure 9. The decadal variation in the average Hs is less than 0.1 m, but the variation in maximum Hs in different decades are up to 1.5 m. At most of the locations in the western shelf seas, high Hs is during 1990-99, mainly due to the storm in June 1996. During the 1996 storm, the maximum Hs measured at location 6 is 6.17 m and during the same event, Hs of 5.69 m is measured by a Datawell directional waverider buoy moored at 23-m water depth off Goa (Kumar et al. 2006), which is 54 km north of the location 6. At locations 1 and 2, the maximum Hs is during the tropical cyclone 03B which lasted from 21st June 2007 to 26th June 2007. At locations 9 and 10, the maximum Hs is during the 5-9 May 2004 cyclone (Rameshkumar and Byju, 2010). The maximum Hs at location 18 to 21 is during the 21-25 November 1995 storm. At location 13 and 14, the maximum Hs is during the 12-16 June 1996 storm. The study shows that even though the maximum Hs values are influenced by the storms/cyclones, the annual average Hs is not significantly influenced by these severe events.

#### **4. Conclusions**

The seasonal response of significant wave height and the long-term trend using the ERA-interim reanalysis dataset is studied during 1979 to 2012. The maximum significant wave height observed is 6.3 m in the western continental shelf and 5.5 m in the eastern continental shelf. Based on long-term trend in wave climate, we can divide the Arabian Sea as three, northern region of increasing trend, middle region of decreasing trend and southern region of increasing trend. During 1979 to 2012, the average trend for all the locations in the western shelf seas is 0.06 cm/year and that for the eastern shelf seas is -0.02 cm/year and are negligible. Even though the maximum significant wave heights are influenced by the storms/cyclones, the annual average value is not significantly influenced by these severe events. The analysis of wind-sea and swell parameters and data with longer duration are required for better understanding of the climate variability in the wave field.

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Table 1. The annual average value of significant wave height, wave period, wind speed and wave length at the locations studied

Location	Position	significant wave height, $H_s$ (m)	wave period, $T_e$ (s)	Wind speed (m/s)	water depth (m)	wave length (m)
1	22.50° N;68.25° E	1.3	7.4	6.1	55	85
2	21.00° N; 69.00° E	1.4	7.9	6.0	600	97
3	19.50° N; 71.25° E	1.3	7.5	5.8	70	88
4	18.00° N; 72.00° E	1.4	8.0	5.4	75	100
5	16.50° N; 72.75° E	1.3	8.0	5.1	70	100
6	15.00° N; 73.50° E	1.3	8.1	4.6	60	102
7	13.50° N; 73.50° E	1.4	8.3	4.9	150	107
8	12.00° N; 74.25° E	1.3	8.3	4.4	1100	107
9	10.50° N; 75.00° E	1.3	8.4	4.4	2000	110
10	09.00° N; 75.75° E	1.3	8.5	4.4	300	113
11	07.50° N; 77.25° E	1.6	8.5	6.4	100	113
12	10.50° N; 81.00° E	0.9	5.9	6.1	3000	54
13	12.00° N; 81.00° E	1.1	6.4	5.8	3300	64
14	13.50° N; 81.00° E	1.0	6.5	5.2	3000	66
15	15.00° N, 81.00° E	1.0	6.5	5.6	2500	66
16	16.50° N, 83.00° E	1.2	7.7	5.8	2000	92
17	18.50° N; 85.00° E	1.4	8.1	5.2	600	102
18	19.50° N; 87.00° E	1.4	8.6	5.5	1500	115
19	20.25° N; 88.50° E	1.4	8.6	5.4	200	115

## Figures captions

Figure 1 Map showing the 19 locations considered in the study

Figure 2. Scatter plot of measured significant wave height with ERA-Interim data for a) Arabian Sea during May-December 2005 and b) Bay of Bengal during July 2004 to May 2005

Figure 3. Variation in monthly average Hs along the western shelf seas of India

Figure 4. Variation in monthly average Hs along the eastern shelf seas of India

Figure 5. Variation of annual mean Hs along the western shelf seas of India. The dotted line indicates the trend in Hs during 1979 to 2012.

Figure 6. Variation of annual mean wind speed along the western shelf seas of India. The dotted line indicates the trend in Hs during 1979 to 2012.

Figure 7. Variation in monthly average Hs along the eastern shelf seas of India. The dotted line indicates the trend in Hs during 1979 to 2012.

Figure 8. Variation of annual mean wind speed along the eastern shelf seas of India. The dotted line indicates the trend in Hs during 1979 to 2012.

Figure 9. Variation in a) average Hs and b) maximum Hs in different decades at the locations studied

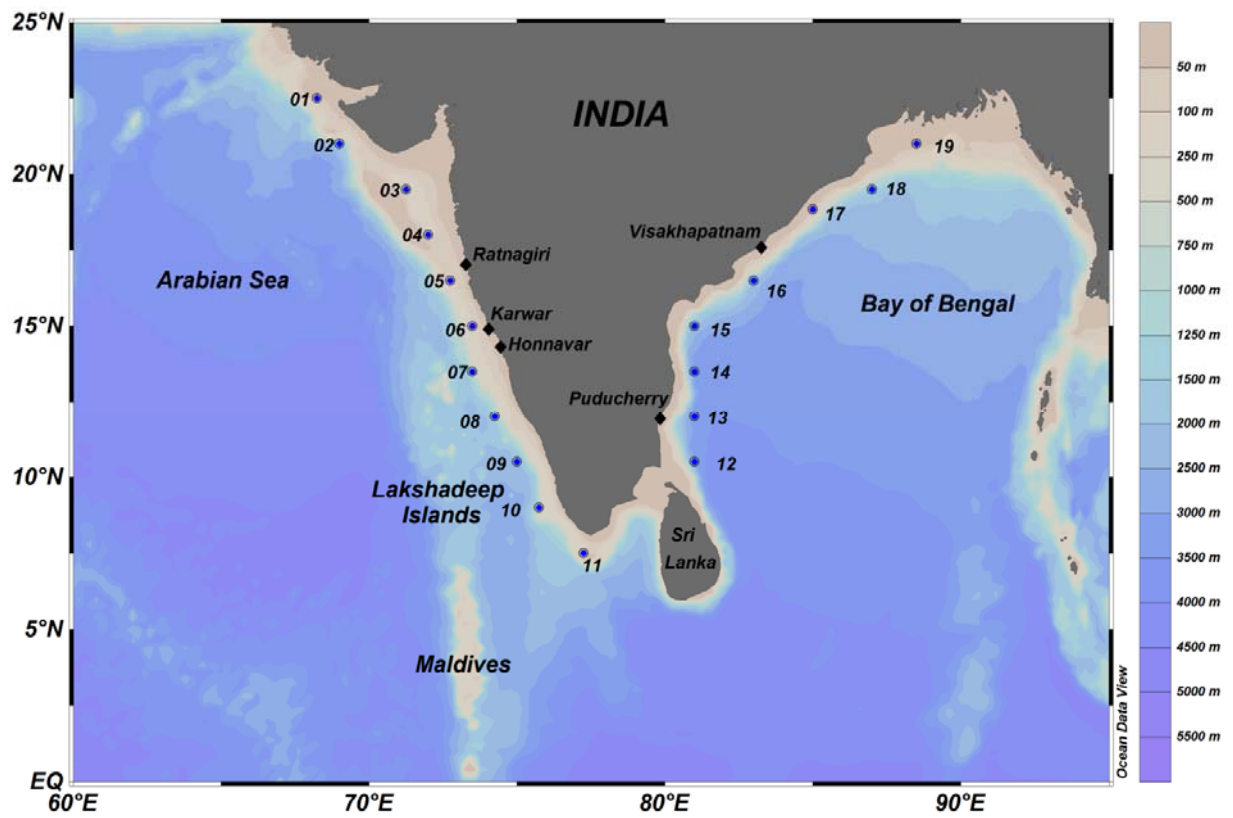


Figure 1 Map showing the 19 locations considered in the study

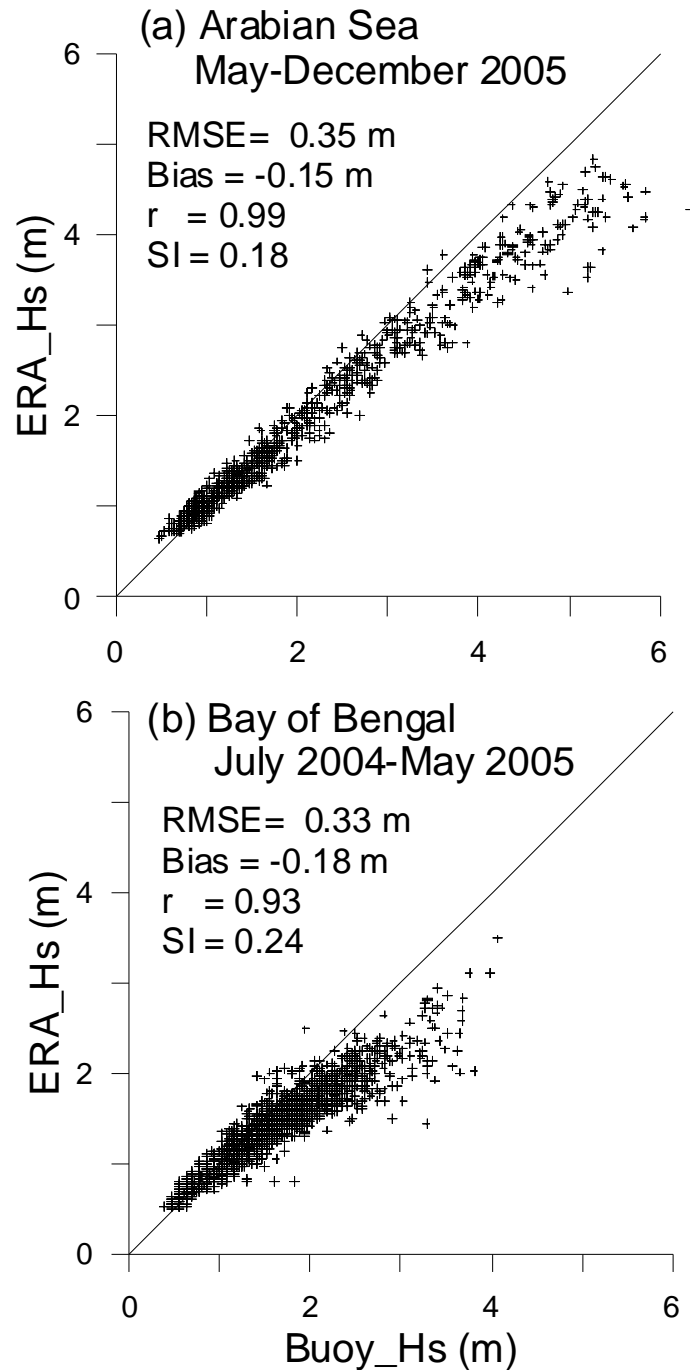


Figure 2. Scatter plot of measured significant wave height with ERA-Interim data for a) Arabian Sea during May-December 2005 and b) Bay of Bengal during July 2004 to May 2005

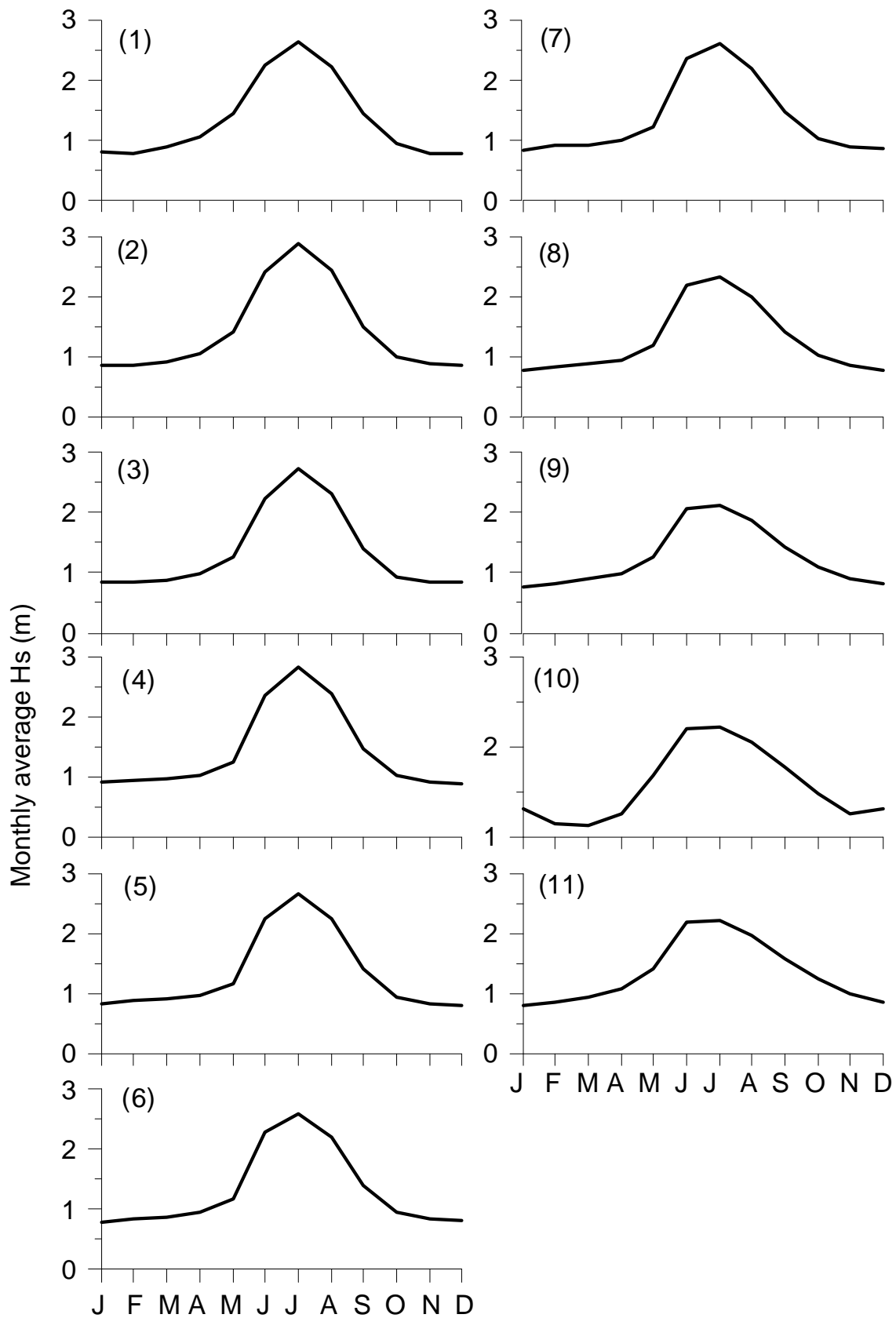


Figure 3. Variation in monthly average Hs along the western shelf seas of India



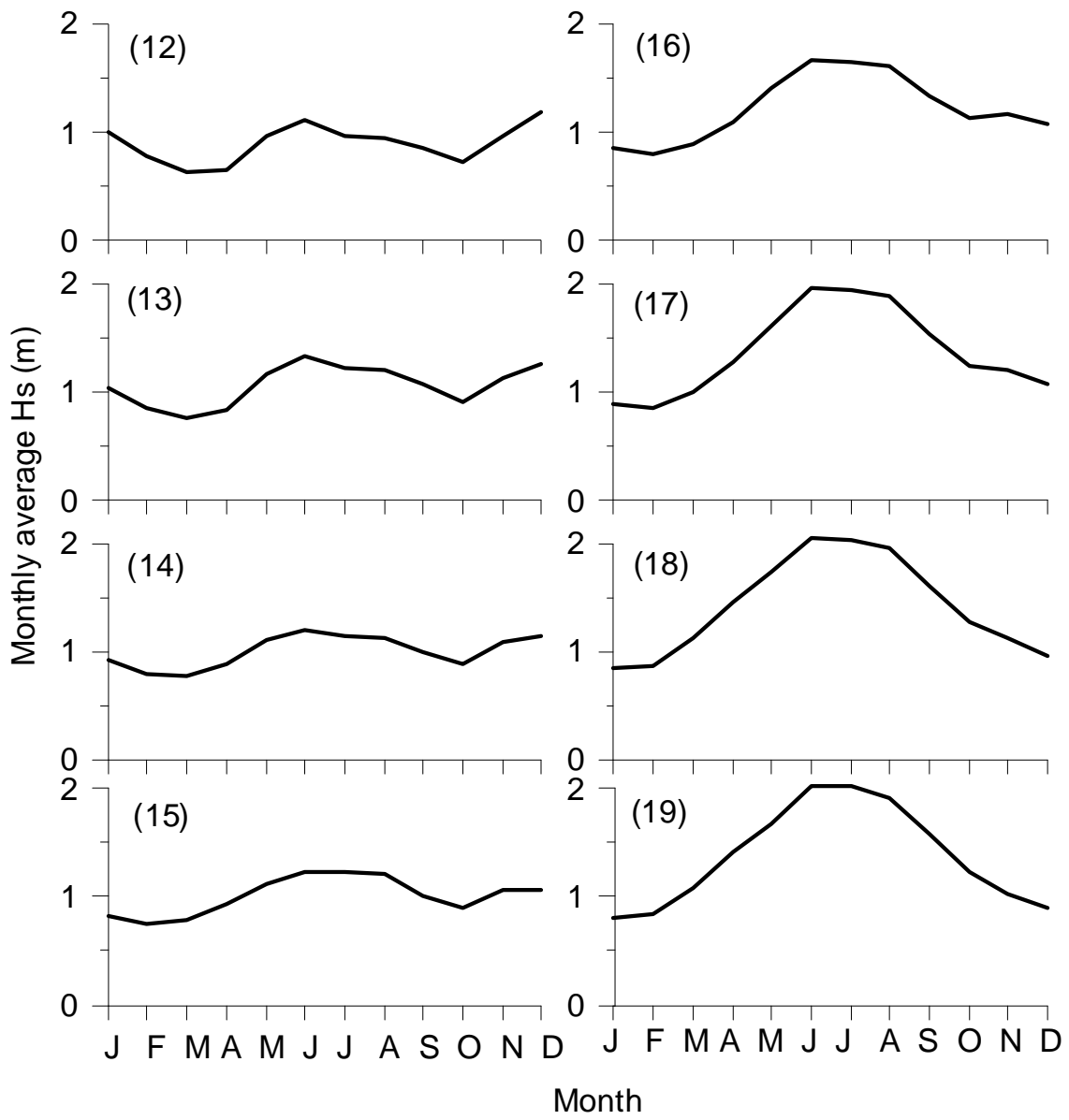


Figure 4. Variation in monthly average Hs along the eastern shelf seas of India during 1979 to 2012

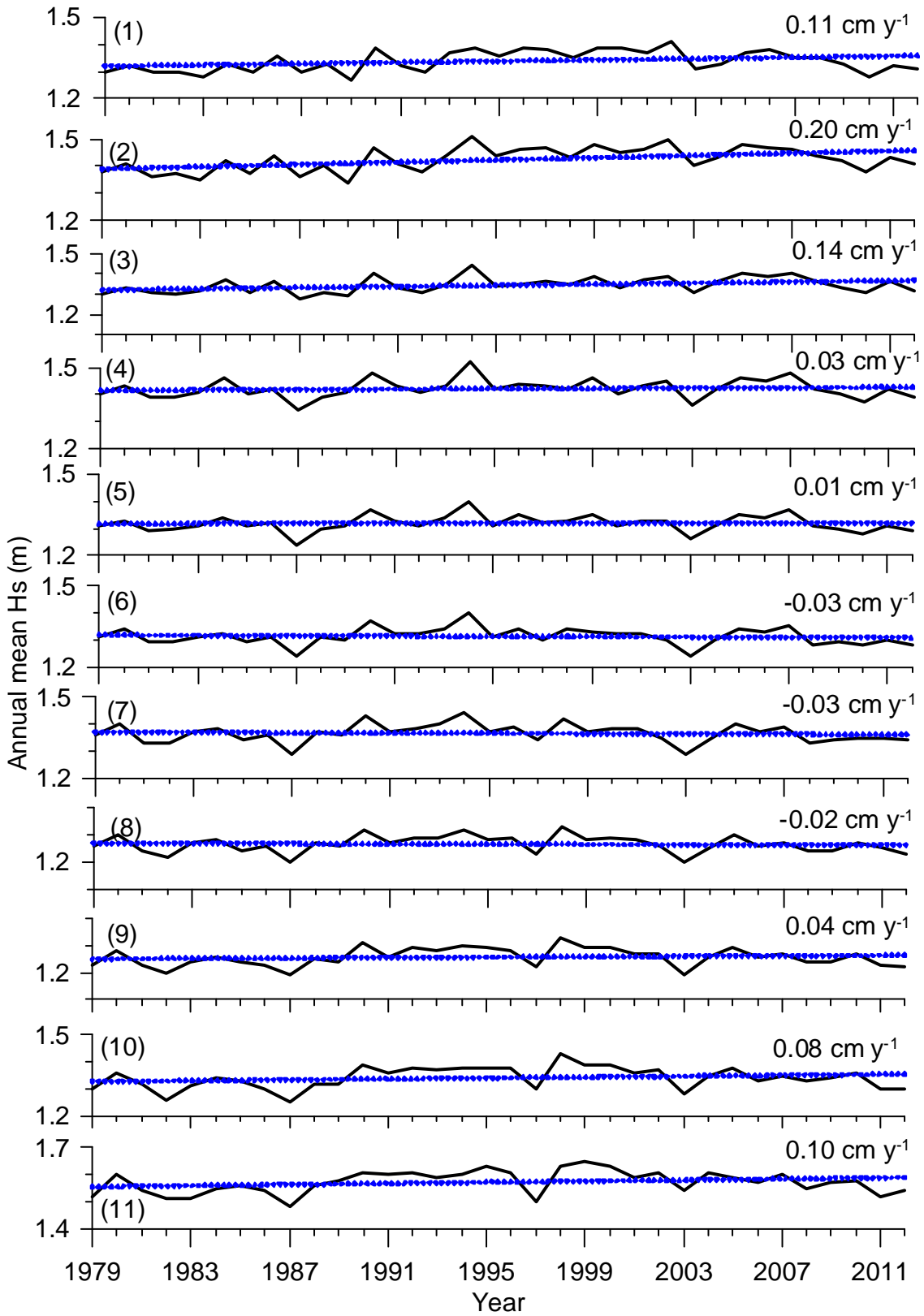


Figure 5. Variation of annual mean Hs along the western shelf seas of India. The dotted line indicates the trend in Hs during 1979 to 2012

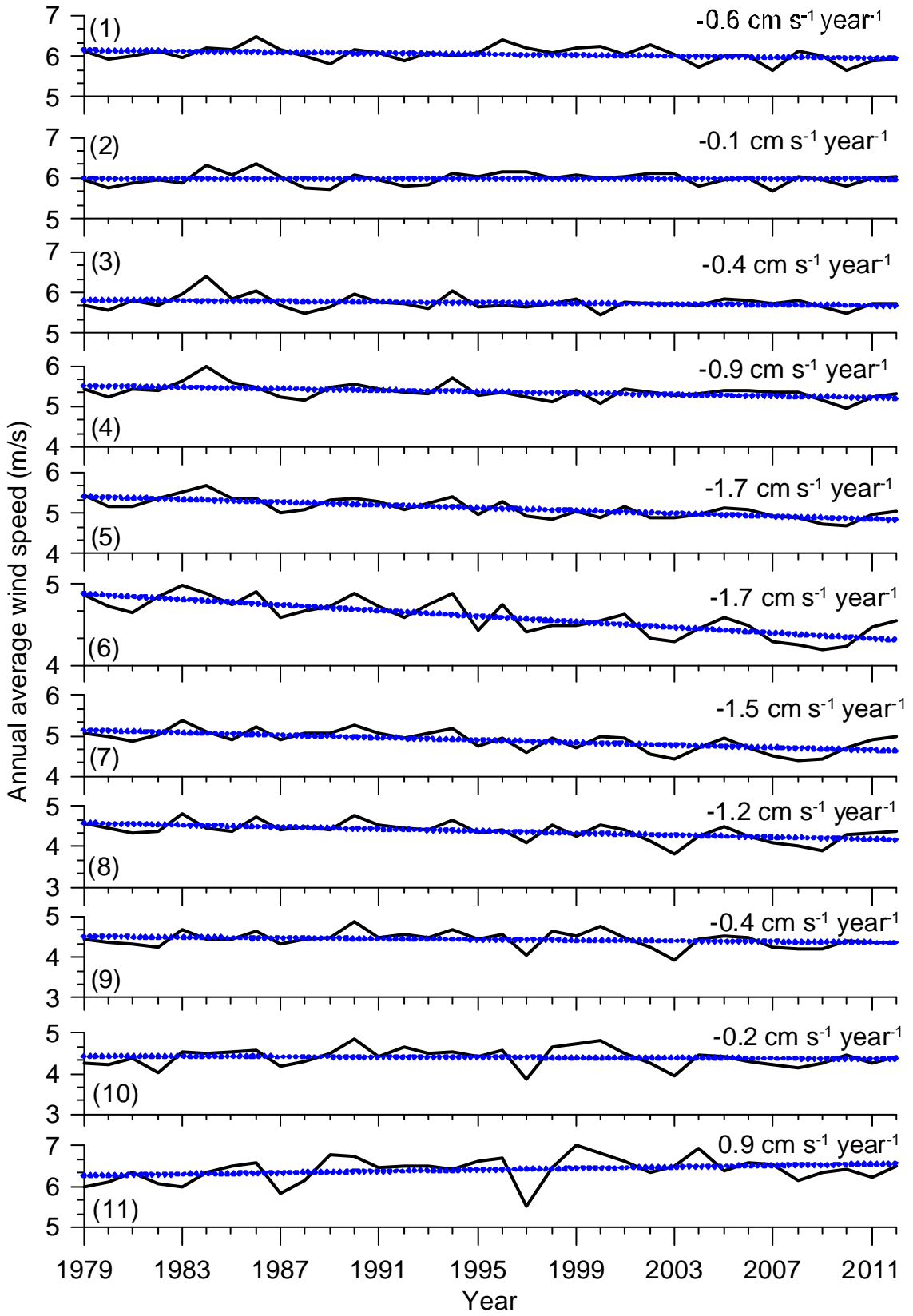


Figure 6. Variation of annual mean wind speed along the western shelf seas of India. The dotted line indicates the trend in wind speed during 1979 to 2012

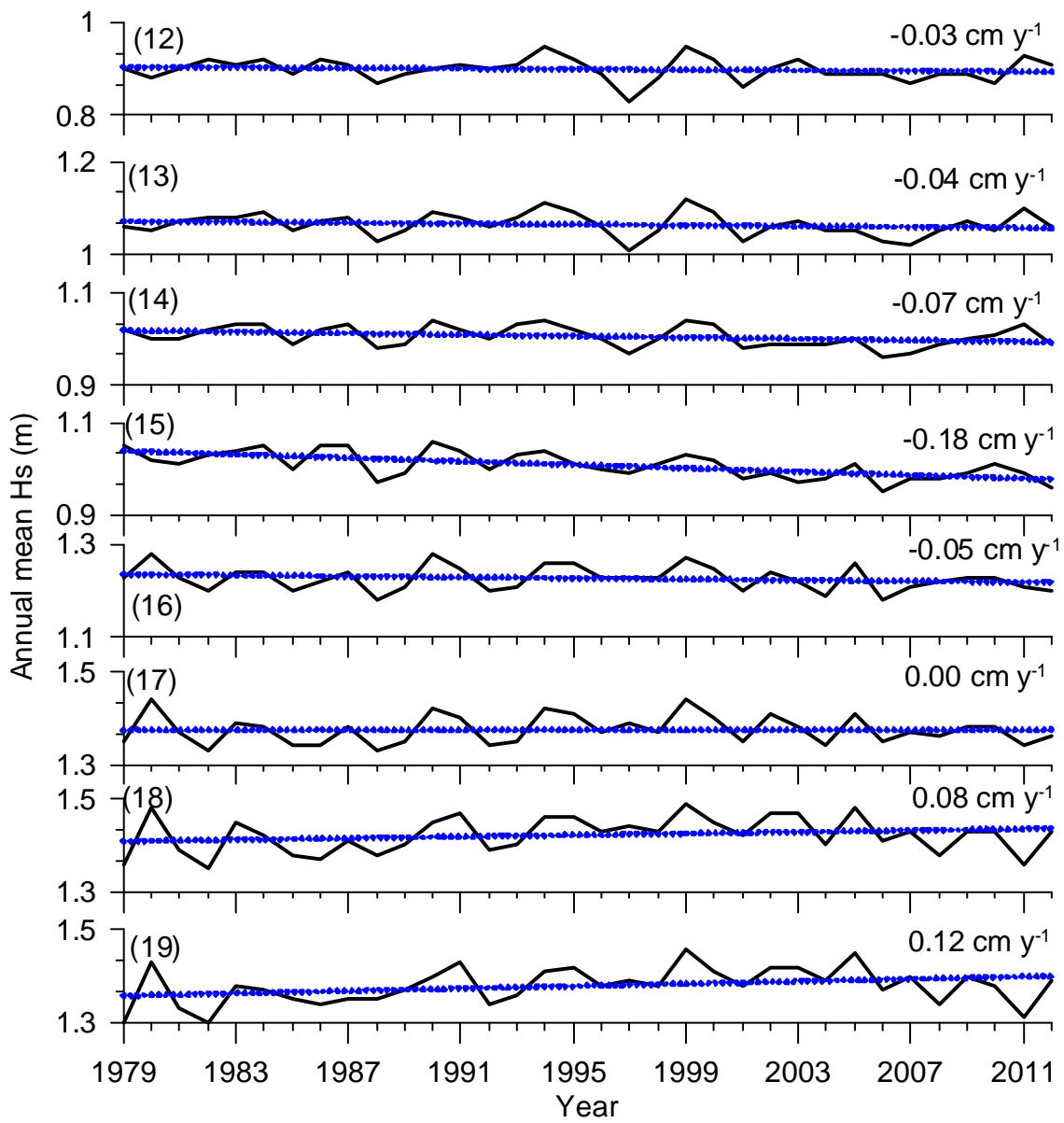
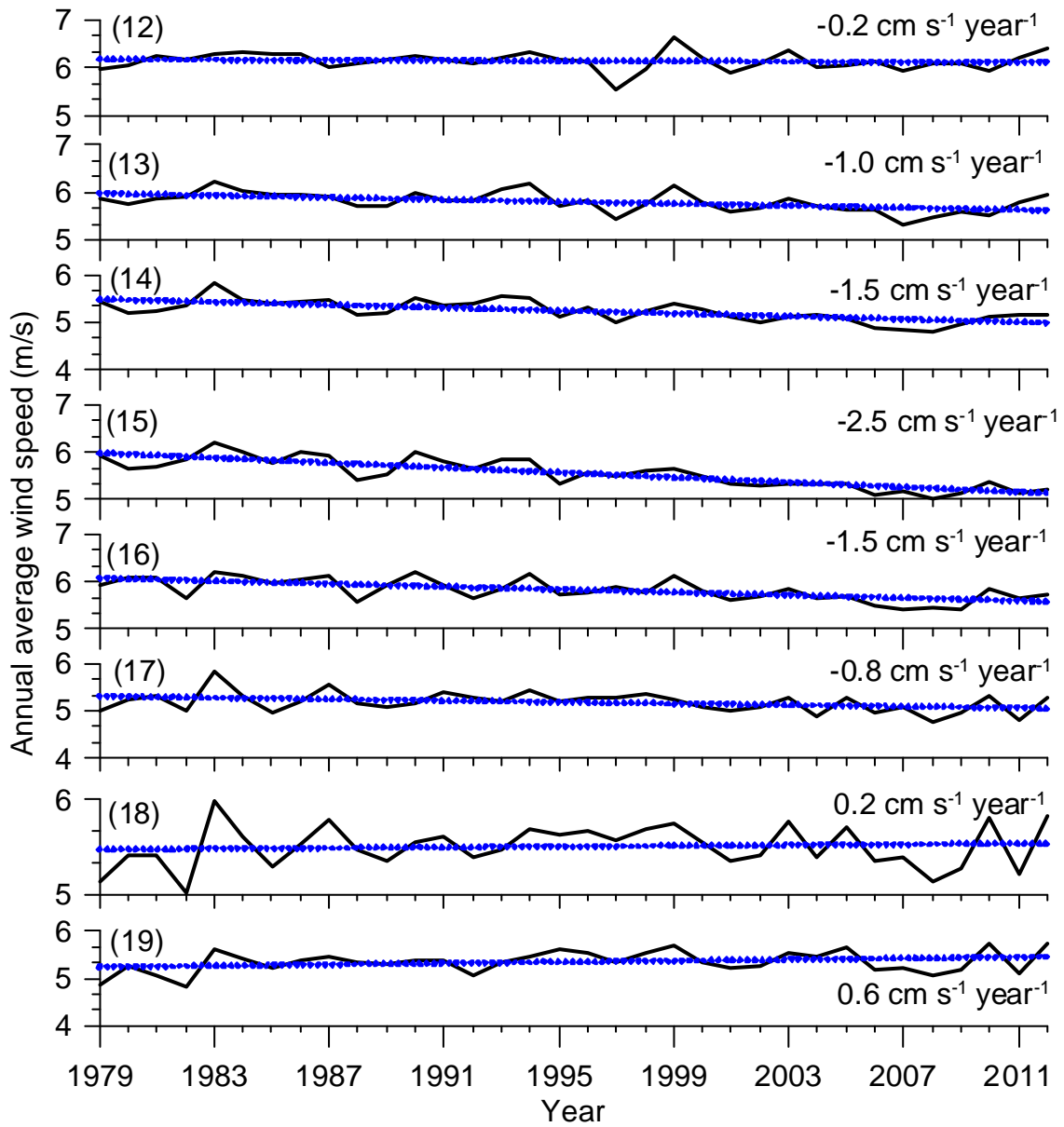


Figure 7. Variation in annual mean Hs along the eastern shelf seas of India. The dotted line indicates the trend in Hs during 1979 to 2012.



. Figure 8. Variation of annual mean wind speed along the eastern shelf seas of India. The dotted line indicates the trend in wind speed during 1979 to 2012

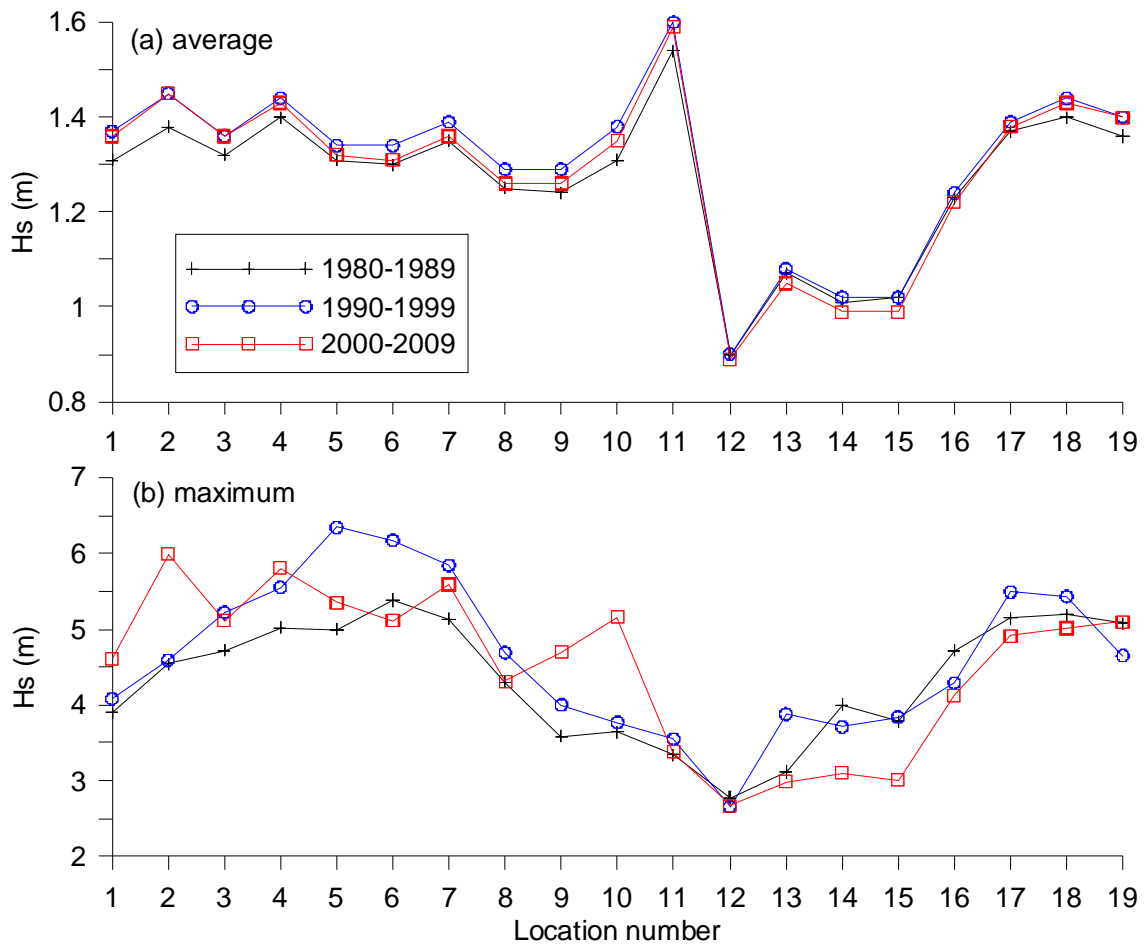


Figure 9. Variation in a) average Hs and b) maximum Hs in different decades at the locations studied