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An empirical model for wave field in Bombay High Area

B. SHYAMALA

Regional Meteorological Centre, Colaba, Bombay

and

B. G. IYER

Shri Chinai College of Commerce and Economics, University of Bombay

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सार — इस शोध पत्र में बम्बई हाई क्षेत्र में अनुमानिक मॉडल द्वारा तरंग सम्बन्धित अध्ययन किया गया है। यह अध्ययन 1976 से 1985 में मई-अक्टूबर महीनों में प्राप्त आंकड़ों पर आधारित है, जब तरंगों की ऊंचाई तथा तीव्रता रिग पर काम करने की सीमा को पार कर जाती है।

यह देखा गया है कि मई-अक्टूबर के समय चक्रवात रहित दशा में औसत ऊंचाई के पूर्वानुमान के लिए वायुगति तथा तरंग ऊंचाई के बीच रैखिक सम्बन्ध, विभिन्न प्रकार के सम्बन्धों की तुलना में पर्याप्त है। इस पत्र में तरंग की दिशा और स्थिरता का भी अध्ययन किया गया है।

ABSTRACT. The work presents an empirical model for wave-field in Bombay High Area (BHA) based on data from 1976 to 1985 for the months, May-October, when the conditions generally exceed the critical limits of the operations of the rigs.

It is seen that in non-cyclonic conditions during May-October, among various forms of relationships between windspeed and wave-heights, the linear fit estimates are found to be quite adequate for the purposes of forecasting mean-height. A study of direction of waves and their steadiness is also dealt with.

1. Introduction

Weather forecasting service for offshore oil-drilling operations is becoming increasingly important since wind and wave-fields are crucial in rig movements, in evacuation of personnel in cyclonic situations, platform constructional activities and for maintaining supplies. The drilling rigs in Bombay High Area (BHA) have the constraints among many others that the height of the wave system should not exceed 8 ft (2.44 m) during voyage and 6 ft (1.85 m) during jack-up and the period of the wave should not exceed 8 seconds during voyage. Due to these critical limits for operation, the Oil and Natural Gas Commission (ONGC) requires weather forecasts including expected wind-field (speed and direction), wave characteristics (height and period), weather and visibility conditions 48 to 72 hours in advance. A meteorological unit was set up under Regional Meteorological Centre, Bombay in 1976 for issuing these special weather forecasts to ONGC for their operations in the Bombay High Area covering approximately 15000 sq. km. The BHA lies over Arabian Sea about 100-250 km west of Bombay.

Initially, in the absence of suitable models for the area, empirical relationships relating wind and wave-field based on observations from other seas of the world were used for issuing the forecast (WMO 1976). Since the verification of the forecasts can be achieved only through real-time actual observations, a data collection system from the ONGC rigs in the BHA has been evolved from 1976. Using this 10-year data set from 1976-85, this paper attempts to establish a relationship between wind speed and wave-height in Bombay High Area with a view to developing a suitable forecasting model for the area.

The frequency distribution of the directions of the waves is also studied. The mean wave directions and their steadiness are worked out.

2. Previous study

Perhaps due to paucity of data, not many works based on actual observations are found on the subject. Mukherjee and Sivaramakrishnan (1980, 1982, 1983) and Sivaramakrishnan (1984) have made synoptic study of the problem based on data from 1976 to 1979. Some authors have advocated approximate formula relating windspeed (V) and wave-height (H) in the form : $H = k\ V^a$, where a and k are constants.

Bretschneider (1957) has suggested the square formula. Thiruvengadathan (1984) recommended a quadratic relation for the mean-wave height (y) of the form: $y = a + bx + cx^2$, where x is the windspeed and obtained the values of the constants $a=0.17$, $b=0.87 \times 10^{-2}$ and $c=1.4167 \times 10^{-2}$ from the data recorded over the Indian seas by Russian vessels during Ismex-1973 and Monex-1977. Using a range of windspeed 6 to 19 mps, he obtained a root-mean-square deviation (RMS) of less than 0.1 m (0.33 ft) during monsoon season. However, the application of this formula using the same values of the constants for BHA for the period 1976-85 gives a root-mean-square error of 3.1 ft for the windspeed range 5 to 33 kt.

The present study differs from the others because (*i*) the observational data are obtained from same specified area of BHA in contrast to data collected from different ships at different parts of the Indian Ocean, in the Arabian Sea and the Bay of Bengal as used in other works (This difference is of operational significance from the point of view of forecasting principles) and (*ii*) The study is based on a ten-year data with more than 1500 observations from the same area.

3. Data

Two main difficulties that are generally encountered in the analysis of wave-field are the paucity of observational data and the difficulty in differentiating waves from swells especially when both are from the same direction as usually experienced in monsoon season. The observations of wave-heights as reported by the rigs actually refer to characteristic wave-heights of the combined system of sea and swell. Further, there are other factors like duration of wind and fetch, besides windspeed, affecting wave-height. As it is very difficult to obtain data on duration of wind, fetch and other similar factors, the forecaster is often left with only windspeed. Further, wave-heights remain the same (Thiruvengadathan 1984) for given windspeeds during the monsoon season in the Arabian Sea. This is probably because during monsoon season steadiness of wind is quite high and fetch is quite large so that duration and fetch can be assumed to be constant and a direct relationship between wave-height and windspeed can be obtained. Hence, it is felt that a study of windspeed influence alone on wave-height would be a good exercise to start with.

The mean height of the waves in BHA is normally less than 4 ft for the period from November to April and is below the critical limits for the operation of the rigs. The height of the waves reach 15 ft or more in monsoon and, therefore, this study is confined to the period of May to October. The study is further confined to non-cyclonic conditions because the problem becomes more complex in a cyclonic storm situation when other factors like duration of wind and fetch also play important role in determining wave-height. Further, the number of observations with speeds greater than 34 kt in the Arabian Sea has been very few.

From these considerations the observations numbering over 1575 as obtained from daily reports through radio communications between the rigs and the on-shore ONGC offices, for the period of ten years from 1976 to 1985 have been used in the study to develop an empirical model relating windspeed and wave-height in BHA during the months, May-October.

A detailed analysis of another correlated wave characteristic, namely, the wave period is under study and will follow in a subsequent paper.

4. Methodology and results

The rigs in the BHA use the pole with a scale for measuring wave-heights in feet and information about wave period is obtained by counting the number of waves that move past a certain point over a certain interval of time.

Table 1 gives the bivariate distribution of wind-wave in the speed range of 1-33 kt. The windspeed is in knots and the wave-heights in feet as are reported from the rigs. The same units are used in this paper also for easy reference.

The class-interval for the windspeed is 2 kt and that for the wave-height is 1.64 ft (0.5 m). The fractional frequencies are in accordance with the classification of such variables (Ref. *Statistical Methods for Research Workers* by R.A. Fisher). The mean wave-height (y) for each class-interval of windspeed is calculated. The mid-values of the class-intervals of windspeed provide x values. The standard deviation of the wave-height is low approximately 1.6404 ft (0.5 m) up to x=10 kt and range between 1.6404 ft and 3.2802 ft (0.5-1.0 m) up to x = 33 kt so that fetch and duration can be assumed to be constant during May-October. Various forms of relationship such as linear, quadratic, power and logarithmic between windspeeds (x) and mean wave-heights (y) are examined.

Table 2 gives the estimated values of mean wave-height (y_c) from the respective fits for the range 1-33 kt of windspeed, the mid-values of the intervals marked as x. The estimated values are rounded off to 3 decimal places in the final presentation. To assess the goodness of fits, root-mean-square deviation (RMS) and R^2, the square of the coefficient of correlation between the mean-height and their estimated values are compared. Table 3 gives the comparative values of RMS and R^2 for linear, quadratic, exponential, power and logarithmic fits empolying least square method. It can be seen that the best fit for this range of x with minimum RMS is quadratic with RMS = 0.6419560 ft followed by linear (RMS=0.8377123 ft) and exponential (RMS=0.8444567 ft). R^2, however, has been more or less same for all the three and is more than 0.98.

A closer examination of linear fit estimates reveals that while Σd^2, which is the sum of the deviation squares of the observed from the estimated values of mean wave-height for the range 1-33 kt is 10.607643, the contribution to Σd^2 from the extreme values of x, namely 1 and 33 is 5.3917012. Since the windspeeds are generally found to be in the range of 5-31 kt in the Arabian Sea during monsoon season in non-cyclonic situation and also because of the expected inaccuracies in the measurement of windspeed of less than 5 kt, it is felt that a re-examination of the various fits may be appropriate in the range of windspeed, 5-31 kt. Scanty data for windspeed above 31 kt and comparability with other works which have used the range above 4 kt are other considerations for the evaluation of goodness of fits in the revised range of 5-31 kt. This range is adequate for forecasting purposes during monsoon in non-cyclonic conditions. Table 4 gives the estimates of mean wave-heights from different fits for the range of windspeed 5-31 kt. The figures are rounded off to 3 decimal places in the final presentation. Table 5 gives the results for the revised range of windspeed. There is little difference between linear (RMS=0.5025595 ft) and quadratic (RMS=0.5025587 ft) fits, the R^2 value for the two being 0.9822. There has been a drastic reduction in RMS in case of power function $y_c=m'x^{n'}$. However, it is still greater than RMS for linear and quadratic.

TABLE 1

Bivariate table of windspeed (kt) and wave height (ft)

Wave height (ft)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30	30-32	32-34	Total
0-1.64	1	3	2	9.5	10	7.5	1.5											34.5
1.64-3.28	4.5	12.5	23	45	32	28.75	11.25	6.5										163.5
3.28-4.92	13	16.5	18.5	84.5	110.5	81.75	44.75	23	16	5.5	1							415
4.92-6.56	2.5	2	6.5	20.5	48.5	61.5	42.25	50	21.5	11	5	..	2	2				275.25
6.56-8.20	1	1	0.5	4	16.5	25	25.25	33	19.5	14.5	11	7.75	8.5	0.5	..	0.5	0.5	169
8.20-9.84			1	2	3.5	11	24.75	28.5	30.5	26.25	19.75	16.25	7.5	3.5	3	2	..	179
9.84-11.48				0.5	1	1	4.5	13	23	20.25	22.25	27.5	18.5	6	0.5	0.5	..	138.50
11.48-13.12							1	2	10.5	16.25	20.25	33	16	21	4	2	1	127
13.12-14.76									3	1.5	4	6	2	8	4	0.5	1	30
14.76-16.40										2	2.5	5.5	3.5	5.5	2.5	3.5	3	28
16.40-18.04												3	1.5	3.5	..	..	3	11
18.04-19.68													1	1	0.5	0.5	..	3
19.68-21.32													..	..	..	..	..	..
21.32-22.96															1·5	0.5	..	2
22.96-24.60																	1	1
Total	22	35	51.5	166	222	216.50	155.25	156	124	97.25	85.75	99	60	51	16	10	9.5	$N=$ 1576.75
Mean wave-ht (ft)	3. 51	3.421	3.575	3.828	4.425	4.893	5.957	6.802	8.260	9.227	10.182	11.352	10.974	12.654	13.684	13.366	6.012	
S. D. of mean wave-ht (ft)	0.693	1.448	1.502	1.400	1.652	1.880	2.207	2.196	2.613	2.561	2.339	2.237	2.449	2.635	3.500	3.640	3.563	
CV (%)	17.5	42.0	42.0	36 6	37.3	38.5	37.1	32.3	31.6	27.8	23.6	19.7	22.3	20.8	26.3	27.2	22.3	

TABLE 2

Computed values of wave heights y_c (ft) with different fits

Windspeed (kt) (mid-values) (x)	Mean wave-ht in ft (Obs.) (y)	$y_c=a+bx$	$y_c=A+Bx+Cx^2$	$y_c=\alpha\beta^x$	$y_c=mx^n$	$y_c=p+q\log x$
1	3.951	1.968	2.924	3.223	2.114	1.699
3	3.421	2.770	3.367	3.575	3.627	4 583
5	3.575	3.572	3.859	3.966	4.662	5.925
7	3.828	4.375	4.398	4.398	5.499	6.809
9	4.425	5.177	4.986	4.879	6.222	7.468
11	4.893	5.979	5.621	5.413	6.868	7.996
13	5.957	6.781	6.304	6.003	7.454	8.434
15	6.802	7.584	7.034	6.659	7.997	8.810
17	8.260	8.386	7.813	7.387	8.504	9.138
19	9.227	9.188	8.639	8.194	8.980	9.431
21	10.182	9.991	9.513	9.088	9.434	9.694
23	11.352	10.793	10.435	10.080	9.865	9.932
25	10.974	11.595	11.404	11.190	10.280	10.151
27	12.654	12.398	12.421	12.410	10.680	10.354
29	13.684	13.200	13.487	13.760	11.050	10.541
31	13.366	14.002	14.599	15.260	11.420	10.717
33	16.012	14.804	15.760	16.930	11.780	10.881

TABLE 3

RMS and R^2 values for different fits between windspeed x (kt) and mean wave-height y (ft)

Equation	Constants	Σd^2.	d.f.	RMS (ft)	R^2
(1) $y_c=a+bx$	$a=1.5665805$ $b=0.4011458$	10.607643	15	0.8377123	0.9612 ($r^2_{x,y}=0.9618$)
(2) $y_c=A+Bx+Cx^2$	$A=2.7194852$ $B=0.1980434$ $C=0.0059736$	6.1816152	15	0.6419560	0.9774
(3) $y_c=\alpha\beta^x$	$\alpha=3.061$ $\beta=1.053$	10.696608	15	0.8444567	0.9638
(4) $y_c=mx^n$	$m=2.114$ $n=0.4911135$	54.138057	15	1.8997904	0.8683
(5) $y_c=p+q\log x$ (base of log=10)	$p=1.6985547$ $q=6.0467288$	102.15152	15	2.609617	0.6762

Note : $r_{x,y}$=product-moment coefficient of correlation between windspeed (x) and mean wave-height (y), d.f.=degrees of freedom.

TABLE 4

Computed wave height y_c (range of x values 5-31 kt)

Windspeed (kt) (mid-values) (x)	Mean wave ht (ft) (y)	$y_c=a'+b'x$	$y_c=A'+B'x+C'x^2$	$y_c=\alpha'\beta'^x$	$y_c=m'x^{n'}$	$y=p'+q'\log x$	y_c (TVN) (m)	y_c (TVN) (ft)
5	3.575	2.396	2.934	3.739	2.937	5.415	0.2894211	0.9495
7	3.828	3.794	3.793	4.181	3.893	6.318	0.3915345	1.2846
9	4.425	4.652	4.651	4.677	4.804	6.992	0.5247024	1.7215
11	4.893	5.510	5.510	5.230	5.683	7.530	0.6889245	2.2603
13	5.957	6.368	6.368	5.849	6.536	7.978	0.884201	2.9009
15	6.802	7.226	7.227	6.542	7.374	8.363	1.1105319	3.6435
17	8.260	8.084	8.085	7.316	8.183	8.698	1.367917	4.4879
19	9.227	8.942	8.943	8.181	8.982	8.997	1.6563564	5.4342
21	10.182	9.800	9.801	9.149	9.766	9.265	1.97585	6.4825
23	11.352	10.658	10.658	10.230	10.540	9.509	2.3263982	7.633
25	10.974	11.516	11.516	11.450	11.300	9.733	2.7080007	8.885
27	12.654	12.374	12.374	12.800	12.060	9.940	3.1206573	10.238
29	13.684	13.232	13.231	14.320	12.790	10.131	3.5643683	11.694
31	13.366	14.090	14.088	16.010	13.530	10.310	4.0391337	13.252

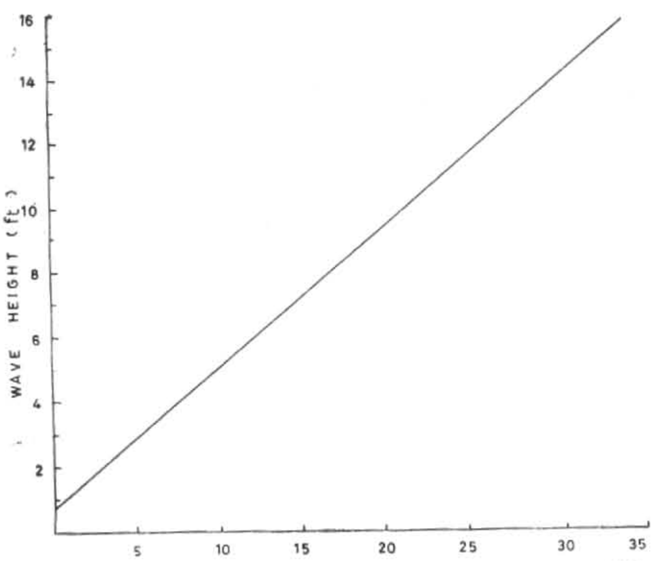
Note : y_c (TVN) = Computed with formula of Thiruvengadathan

TABLE 5

RMS and R^2 values for different fits between windspeed x (kt) and mean wave-height y (ft)
(Range of windspeed 5-31 kt)

Equation	Constants	Σd^2	d.f.	RMS	R^2
$y_c=a'+b'x$	$a'=0.7904114$ $b'=0.4290208$	3.0307939	12	0.5025595	0.9322 ($r^2_{x,y}=0.9822$
$y_c=A'+B'x+C'x^2$	$A'=0.7865007$ $B'=0.4295644$ $C'=-.0000151$	3.0307844	12	0.5025587	0.9822
$y_c=\sigma'\beta'^x$	$\alpha'=2.827$ $\beta'=1.057$	12.362191	12	1.014979	0.9186
$y_c=m'x^{n'}$	$m'=0.7632$ $n'=0.8373616$	4.025033	12	0.5791540	0.9796
$y_c=p'+q'\log x$ (base of log=10)	$p'=1.0971728$ $q'=6.1775081$	67.416044	12	2.3702328	0.9113

Note : $r_{x,y}$=Product-moment coefficient of correlation between x and y; d.f.=degrees of freedom.



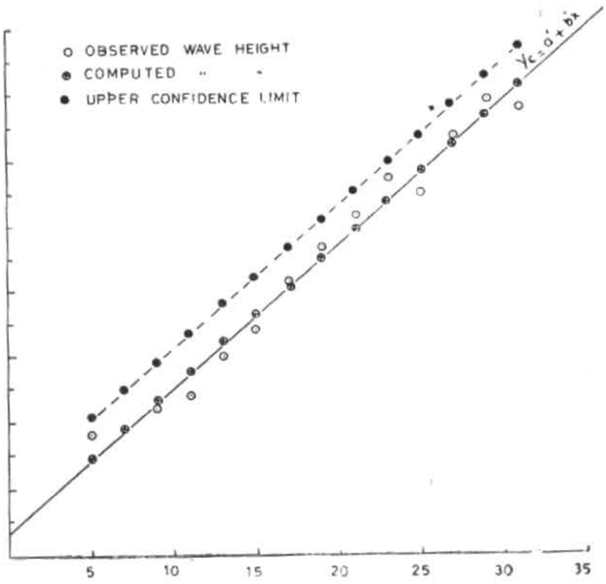


Fig. 1. Nomogram relating windspeed and wave-height for Bombay High Area

Fig. 2. 95% upper confidence belt for mean wave-height

Interestingly, there is great consistency when the quadratic fit is compared with the linear. The constants in the two fits $a' = 0.7904114$ and $A' = 0.7865007$ are almost equal and the term in x has also nearly the same coefficient $b'=0.42090208$ and $B'=0.4295644$. The coefficient of x^2 term in quadratic is very small and negative ($C'=-0.0000151$) and makes negligible contribution to computed values of mean wave-heights for the range of windspeed 5-31 kt. Hence, it may be concluded that the linear fit is quite adequate for the purpose of forecasting mean wave-height in BHA when the windspeed does not exceed 31 kt in non-cyclonic conditions. A nomogram relating windspeed and wave-height in BHA during monsoon seasons in non-cyclonic conditions is given in Fig. 1.

Table 6 gives the limits for the mean wave-heights that will be exceeded for a given windspeed with a probability of 2.5% or less. These values are obtained using a linear regression model of $y_c = a + bx + \epsilon$, where ϵ denotes the random element. In prediction, individual events are predicted, not values of $a + bx$ and hence, the random element. The root-mean-square of y_c used in the fiducial limits is :

$$S_y = \sqrt{\frac{\Sigma\, d^2}{n-2}\left(1 + \frac{1}{n} + \frac{(x-\bar{x})^2}{\Sigma\,(x-\bar{x})^2}\right)}$$

where n = No. of observations in the bivariate data of windspeed and mean wave-height and $\bar{x}$ = mean of windspeed.

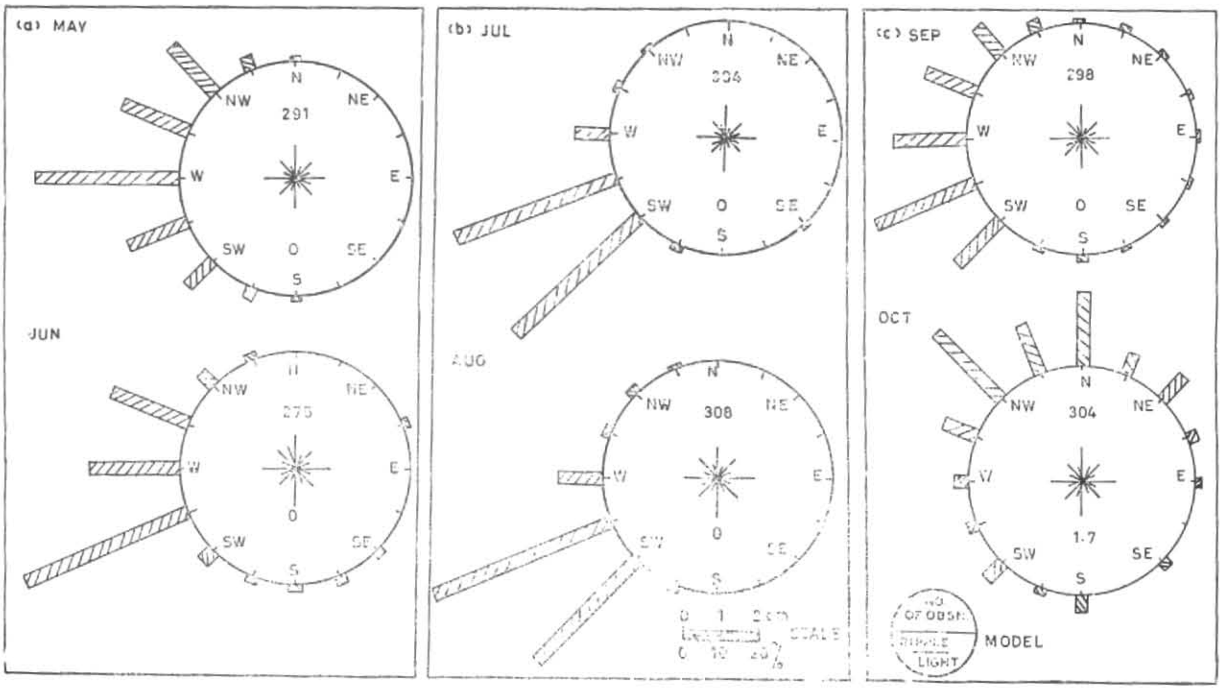
Fig. 2 shows the estimated values of the mean wave-heights from the linear fit $a + bx$ along with the upper confidence belt for $y_c = a + bx + \epsilon$ that will be exceeded by mean wave-heights with a probability of 2.5% or less. This can be conveniently used as a

TABLE 6

95% confidence limits for mean wave-height

(Range of windspeed 5-33 kt)

Windspeed (mid values) (kt)	Estimated mean wave-ht (ft) $y=a'+b'x$	Observed mean wave-height (ft)	Upper confidence limit for mean wave-ht (ft)
5	2.936	3.575	4.163
7	3.794	3.828	4.995
9	4.652	4.425	5.831
11	5.510	4.893	6.673
13	6.368	5.957	7.516
15	7.226	6.802	8.364
17	8.084	8.260	9.218
19	8.942	9.227	10.076
21	9.800	10.182	10.939
23	10.658	11.352	11.806
25	11.516	10.974	12.678
27	12.374	12.654	13.554
29	13.232	13.684	14.434
31	14.090	13.366	15.318



Figs. 3(a-c). Wave rose diagram for Bombay High Area for May-October (1976-85)

TABLE 7

Frequency distribution of wave direction based on data from 1976 to 1985

Month	Rippled/ Light	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total No. of obsn.	Data not available	Total
May	0	1	0	0	0	0	0	0	0	1	7	24	46	107	51	46	8	291	19	310
(%)	0	0.3	0	0	0	0	0	0	0	0.3	2.4	8.2	15.9	36.9	17.5	15.8	2.7			
Jun	0	0	0	2	0	0	2	3	1	2	9	122	63	58	11	2	0	275	25	300
(%)	0	0	0	0.7	0	0	0.7	1.1	0.4	0.7	3.3	44.4	22.9	21.1	4.0	0.7	0			
Jul	0	0	0	0	0	0	0	1	0	0	2	133	133	28	5	2	0	304	6	310
(%)	0	0	0	0	0	0	0	0.3	0	0	0.7	43.8	43.8	9.2	1.6	0.6	0			
Aug	0	0	0	0	0	0	0	0	0	0	3	110	150	34	6	4	1	308	2	310
(%)	0	0	0	0	0	0	0	0	0	0	1.0	35.8	48.8	11.1	2.1	1.9	0.3			
Sep	0	2	4	4	3	3	2	1	1	4	3	46	84	58	43	30	10	298	2	300
(%)	0	0.7	1.3	1.3	1.0	1.0	0.7	0.3	0.3	1.3	1.0	15.5	28.2	19.5	14.4	10.1	3.4			
Oct	5	55	15	23	5	1	0	4	0	12	3	18	6	12	29	75	41	304	6	310
(%)	1.7	18.1	4.9	7.6	1.7	0.3	0	1.3	0	4.0	1.0	5.9	2.0	3.9	9.5	24.6	13.5			

TABLE 8

Mean wave direction and its steadiness

Month	Mean wave direction	Percentage steadiness
May	274° (W)	84.0
June	241° (WSW)	86.1
July	239° (WSW)	91.1
August	243° (W)	90.8
September	266° (W)	72.0
October	329° (NNW)	58.6

nomogram for forecasting 95% upper confidence limit of wave-height in BHA in the monsoon season in non-cyclonic situation when fetch and duration of wind are constant and the mean wave-height shows very low scatter. The values of mean wave-heights computed from the bivariate table are also plotted. It can be seen that all these values lie within the Upper Confidence Belt.

Table 7 gives the frequency distribution of wave direction in a 16-point compass scale for the data from 1976 to 1985. In May, the waves are observed mostly in sector SW to NW on 94.1% of the occasions. In June, July and August the wave-sector narrows down to the direction of SW to W with frequencies of 88.4%, 96.9% and 95.4% respectively. During September, the waves are found to occur in SW to NW sector 87.6% times. In October, though the waves appear to be scattered in almost all directions, the sector W to NE through N has a wave frequency of 80% (Figs. 3 a-c).

Table 8 indicates the mean direction of the waves with percentage steadiness during May to October.

The mean wave direction backs from westerly in May to WSW in June, July and August and then veers to westerly in September and to NNW in October.

The steadiness of the wave direction is maximum in the mid-monsoon months of July and August (about 91%) and it is minimum in the transition month October. In the pre-onset phase in May, the steadiness of the wave direction is 84% and during the onset phase in June, the percentage is 86.

5. Conclusions

(*i*) Quadratic, linear and exponential are good fits for mean wave-heights in BHA for the windspeed of range 1-33 kt though quadratic seems to be better than the other two.

(*ii*) For the revised range of 5-33 kt which is adequate for forecasting purposes during monsoon in non-cyclonic conditions and which also reduces the possibility of expected inaccuracies and scanty data, there is little difference between quadratic and linear fits so that the linear model can be taken to represent the wind wave-field in BHA during monsoon season in non-cyclonic conditions. The other fits have greater RMS.

(*iii*) The mean wave-heights (y_c) computed from the observed values lie within the upper confidence belt which gives the limits for the mean wave-heights that will be exceeded with a probability of 2.5% or less in a regression model of $y_c = a + bx + \epsilon$, where, ϵ denotes the random element.

(*iv*) Waves over BHA back from westerly in May to WSW in June, July and August and then veer to westerly in September and to NNW in October.

(*v*) The percentage steadiness of the wave direction increases in the pre-onset and onset phases of monsoon and reaches a maximum of about 91% during July and August. Thereafter, it decreases and reaches to a minimum of 58.6% in October.

(*vi*) The nomogram based on the linear estimates and the frequency distribution of wave direction along with its steadiness can be conveniently put to operational use for issuing forecasts to BHA.

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