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Wind and wave regime over the Bombay high area under the influence of cyclonic storms

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सार - इस शोध - पत्र में चक्रवात की अवधि में मुम्बई हाई क्षेत्र (बी.एच.ए.) में वायु वेग और समुद्री लहरों की सामायिक स्थितियों का अध्ययन किया गया है। अध्ययन के लिए चक्रवात की अवधि के बी.एच.ए. के दस वर्षों (1990-99) के आँकड़ों का उपयोग किया गया है। अध्ययन के दौरान यह देखा गया है कि मानसून पूर्व की अवधि में चक्रवाती तूफानों के प्रभाव के कारण बी.एच.ए. में दक्षिण पूर्वी पवनें तीव्र वेग से चलती है तथा मानसून अवधि के पश्चात् दक्षिण-पूर्वी पवनें अपेक्षाकृत कम वेग से चलती है। बी.एच.ए. में मानसून पूर्व की अवधि में दक्षिण पूर्वी पवनों के साथ 20 फीट से भी अधिक उँची की समुद्री लहरें उठती हैं तथा मानसून अवधि के पश्चात् दक्षिण-पूर्वी पवनों के साथ 12 फीट तक की उँचाई की समुद्री लहरें उठती हैं। तूफान की विभिन्न अवस्थितयों के आधार पर किए गए विश्लेषणों से भी इसी प्रकार के परिणाम प्राप्त हुए हैं। बी.एच.ए. में पवन वेग और समुद्री लहरों की उँचाई के साथ तूफान के केन्द्र की दूरी के परस्पर संबंधों का भी अध्ययन किया गया है।

ABSTRACT. Temporal distributions of wind and wave over Bombay High Area (BHA) during cyclone period have been studied. Ten years' (1990-99) data of BHA during cyclone period have been used. It is found that under the influence of cyclonic storms strong southwesterly winds prevail over the BHA in pre-monsoon and weaker east to southeasterly winds during post-monsoon. Southwesterly wave with heights exceeding 20 feet are encountered in BHA during pre-monsoon and south easterlies with wave height reaching up to 12 feet in post monsoon. Analysis of situations with different storm locations also yielded similar results. Relationships between wind speeds and wave height as well as the distance of the storm centre over BHA have been established.

Key words – Cyclonic storm, Bombay high area, Wave, Wind.

1. Introduction

Extensive offshore drilling and exploration operations in Arabian sea necessitate a comprehensive understanding of the wave and wind regime of the area. Wave characteristics in the open sea depend upon the strength of wind, its fetch and duration. According to Bhandari (1980) swell should not exceed 1.5 to 2.0 m (5-7 feet) for smooth operation and safe movement of the jack up rigs. A wind speed of 20 knots is the corresponding critical limit to generate wave height of 1.6 to 2.4 m (5-8 feet) (Thiruvengadathan 1984 & Sivaramakrishnan 1984). Various researchers have studied these parameters and empirical relationships have been obtained on the basis of observational data.

Mukherjee and Sivaramakrishnan (1980 & l982) studied some aspects of swell based on observations over BHA made by the Oil and Natural Gas Corporation Limited (ONGCL) rigs during monsoon seasons of 1976 to 1978. Thiruvengadathan *et al.* (1984) studied the climatological behavior of swells over the Arabian Sea during monsoon by utilizing swell reports from Russian research vessels during three years. Shyamala *et al.* (1989) have tried to evolve a relationship between wind speed and wave height in non-cyclonic condition during monsoon season. Bhan *et al.* (1994) applied graphical regression method for predicting wind over BHA, but they could not develop a regression equation between predictants and predictor because their correlation coefficients were very low. All these studies deal with monsoon season or periods devoid of cyclonic disturbance. However, from a forecasters point of view it is under these situations that prediction becomes more difficult as well as critical.

Although, development of the cyclonic storm over the Arabian Sea is a rare occasion, the number of cases are sufficient to deserve specific attention. Of a total of 194

TABLE 1

Cyclonic storm cases along with maximum *T* numbers achieved

	Duration of cyclonic storm over the Arabian Sea	Max *T* No. achieved
	Pre-monsoon season	
Case 1	09 June ′92 - 12 June ′92	2.5
Case 2	05 June ′94 - 09 June ′94	3.5
Case 3	17 June ′96 - 20 June ′96	3.0
Case 4	04 June ′98 - 10 June ′98	4.5
Case 5	16 May ′99 – 20 May ′99	4.0
	Post-monsoon season	
Case 1	01 Oct ′92 - 03 Oct ′92	3.0
Case 2	12 Nov ′93 - 15 Nov ′93	4.0
Case 3	15 Nov ′94 - 19 Nov ′94	3.0
Case 4	12 Oct ′95 - 17 Oct ′95	3.0
Case 5	20 Oct ′96 - 25 Oct ′96	4.0
Case 6	1l Oct ′98 - 17 Oct ′98	2.5
Case 7	13 Dec ′98 - 17 Dec ′98	3.5

storms which evolved during 1900-99 over the Arabian Sea, majority of them originated near the Lakshadweep area in the region bound by 5° -12° N latitudes and to the east of 65° E longitude. Of these, about 38 storms originated in Bay of Bengal and emerged into the Arabian Sea. Gujarat coast is however vulnerable to cyclones with almost two cyclones crossing the coast every decade (India Meteorological Department, 1979 & 1996). Wind and swell associated with the cyclonic storm over the Arabian Sea as well as the BHA are not adequately documented. This makes it difficult to get an estimate of wind & wave experienced over BHA under the influence of cyclone events. In view of the operational importance of improving forecasts of wave characteristics in the BHA under the influence of cyclonic disturbances, this study focuses on wind-wave relationship and climatology during such conditions. The study also incorporates latest data available from an enhanced number of ONGCL rig observation.

2. Data and method of analysis

Wind and wave data collected by the various rigs of ONGCL deployed in BHA for the period from 1990-99 have been used in this study. These observations at the ONGCL rigs are recorded four times a day at 0830, 1130, 1430, 1730 hrs IST, however during disturbed conditions additional observations are also recorded as per requirement. In addition to the data from ONGCL rigs, all ship data in the vicinity of BHA are also utilized in this study.

The duration and other detailed information of the cyclonic storms over the Arabian Sea during 1990-99 have been collected from Annual Cyclone Review reports of India Meteorological Department. Twelve cyclonic storms formed over the Arabian Sea during 1990-99. Details of the duration of the cyclonic storm are shown in Table 1.

In ten years, 12 cyclones had formed over the Arabian Sea of which 5 formed before onset of the southwest monsoon and 7 formed during the post monsoon season. The track of the cyclonic storm formed over the Arabian sea has been prepared and shown in Fig.1. Therefore to study the seasonal variation in wind & wave pattern over the BHA the analysis has been carried out separately for the cyclone cases, which formed before southwest monsoon and after the southwest monsoon season. The wind and wave data were sorted accordingly.

Frequency analyses of wind for wind direction (N, NE, E, SE, S, SW, W, NW) and wind speed under six categories (*i.e.* wind speed < 10; 11-20; 21-30; 31-40; 41-50; and >50 knots) were studied. Similarly frequency analyses of wave for wave direction in eight point and height under five categories (*i.e.* wave height is < 3; 4-6, 7-12, 13-20 and > 20 ft) were carried out.

To study the influence of cyclonic disturbances over BHA, four different situations based on location of the disturbances, and a general situation including all disturbances during the 1990-99 period in the Arabian Sea were considered. The four different categories are as follows

(*i*) Cyclone centered within 500 km in south to west sector from BHA.

(*ii*) Cyclone centered within 500 km in west to north sector from BHA.

(*iii*) Cyclone centered beyond 500 km of BHA.

(*iv*) Low-pressure area/depression, located within 400 km in southwest of BHA on 12 October 1995 to 13 October 1995.

Wind and wave roses have been prepared for all above-mentioned categories. Based on above analysis,

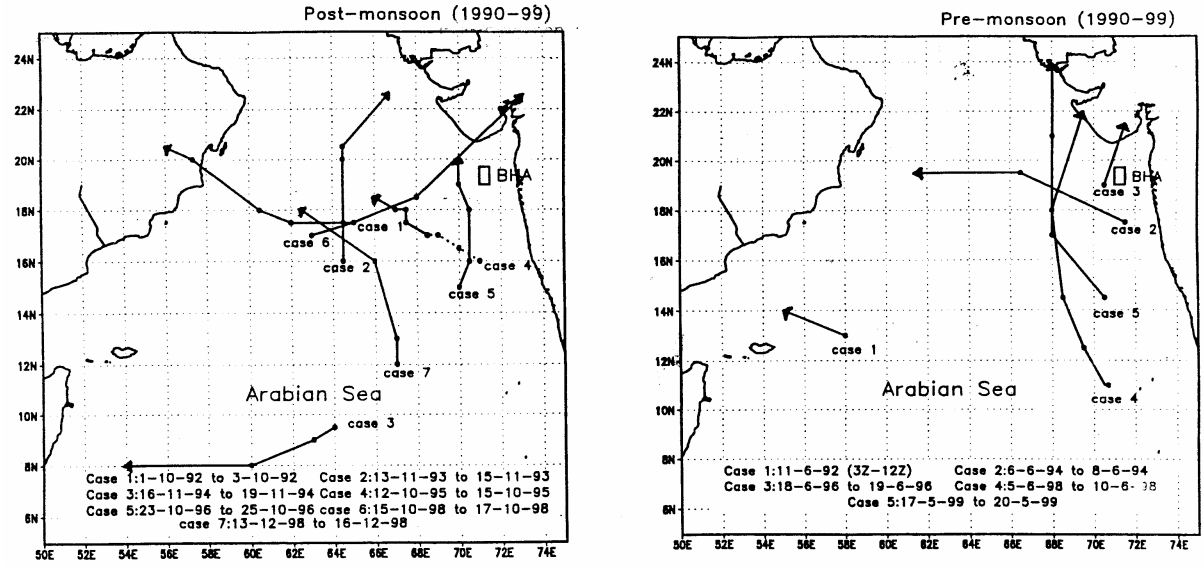

Fig. 1. Tracks of cyclonic disturbances during pre and post-monsoon seasons for 1990-99

wind and wave roses have been prepared for three categories. Similarly wind & wave roses have also been prepared for low-pressure area/depression cases which lies within 400 km from BHA.

To study the relationship between wind speed and wave height over BHA, the analysis of wind speed with respect to wave height were carried out. Relation between wind speeds and wave height was studied using curve-fitting technique. Linear fit was chosen after initial graphical examination. Similarly, relationship between maximum wind speed and distance of the storm centre were also examined and a logarithmic fit was chosen.

3. Result and discussion

3.1. *General case including all cyclonic disturbances in the Arabian Sea*

3.1.1. *Wind*

Cyclonic disturbances in the Arabian Sea result in winds and waves from the southern quadrants. Seasonal wind and wave roses are prepared and presented in Fig. 2. During pre-monsoon, BHA experiences southwesterly winds on 31% and southerly on 29% of occasions. Southeasterly winds are also seen on 18% of occasions. Wind speeds ranging between 21-30 kts were experienced on 23% and on 18% of occasions in 31-40 kts range. Strong wind speed ranging between 41-50 kts was experienced on 9% of the occasions and 6% of occasions recorded wind speed exceeding 50 kts.

During post monsoon, BHA experienced southerly winds on 26%, easterly on 22%, southeasterly on 20% and northeasterly on 15% of the occasions. Wind speeds ranging between 2l-30 kts and 31-40 kts were observed on 16% and 8% of the occasions respectively. Stronger winds exceeding 40 kts are rare. Weaker winds (< 20 kts) were however observed on 67% of occasions.

Therefore, it is concluded that south to southwesterly winds were more predominant in pre-monsoon and east to southerly winds in post-monsoon season. Wind speeds exceeding critical limit of 20 kts were more frequent in pre-monsoon (56%) and were comparatively less frequent (33%) in post-monsoon season. The present analysis based on the ten years data shows that chances of wind speed exceeding 50 kts are more in pre-monsoon and very rare in post-monsoon season. In contrast to the preferred wind direction of south to southwesterly in pre-monsoon, the post-monsoon was dominated by south to southeasterly winds. This may be due to the predominance of westerly component in prevailing winds in pre-monsoon and easterly component in post-monsoon.

3.1.2. *Wave*

In pre-monsoon, southwesterly waves were observed on 48% of occasions. Southerly waves were also

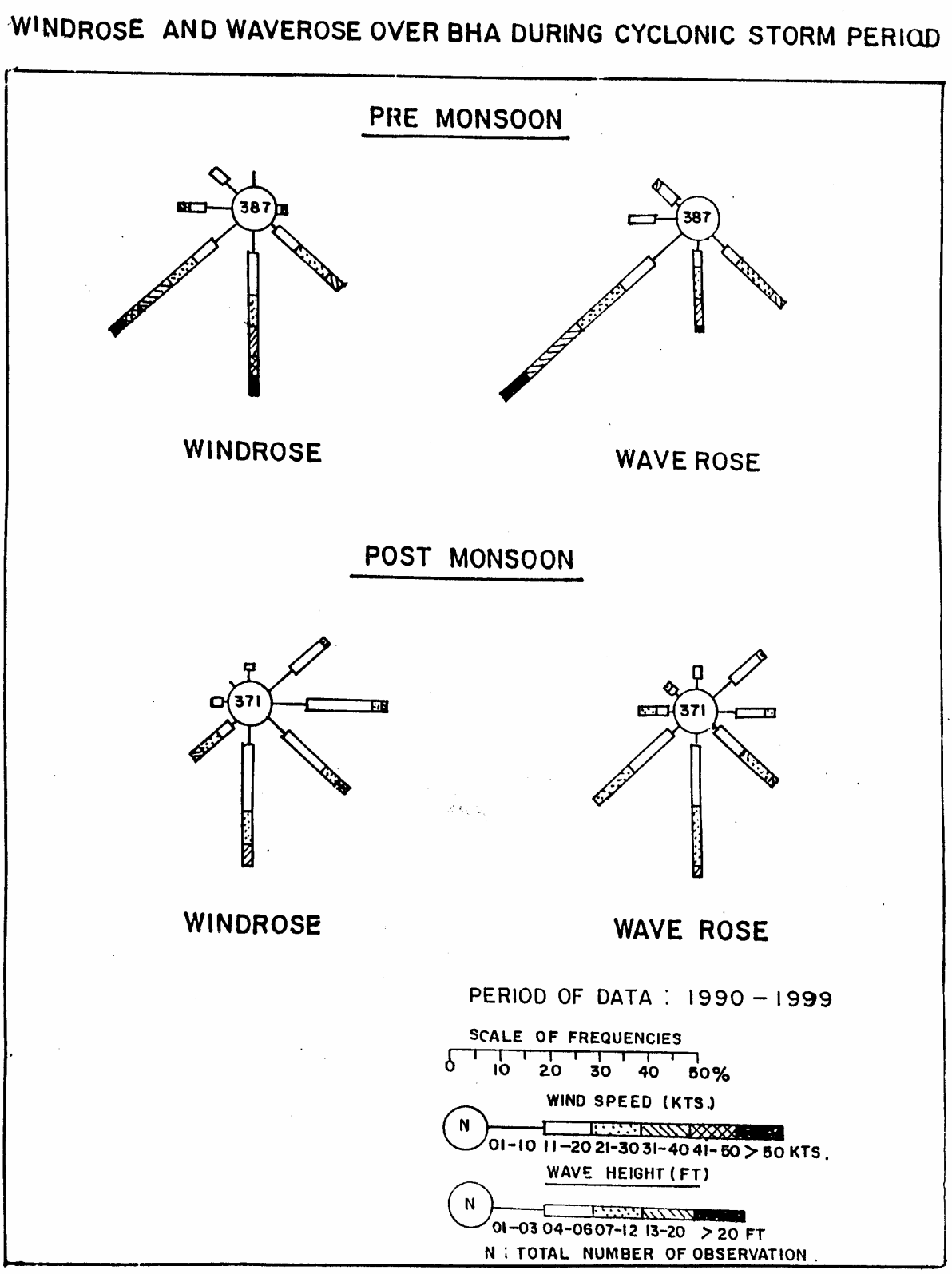

Fig. 2. General case

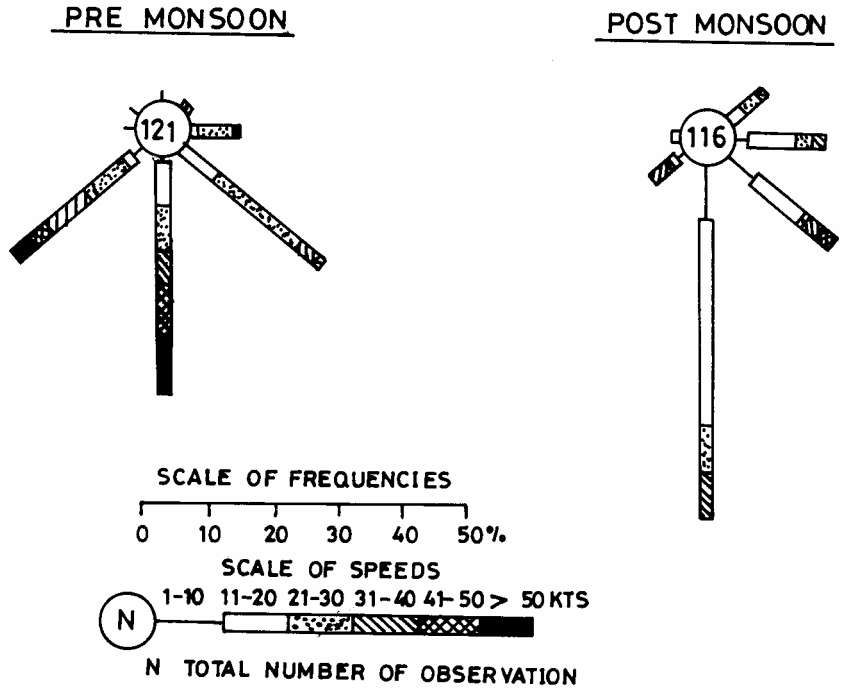

Fig. 3. When cyclone is within 500 km from BHA in southwest sector

experienced on 17% of occasions and southeasterly waves on 18% of occasions. Wave heights ranging between 4.0-6.6 m (13-20 ft) were experienced on 22% and 26% of occasions in 2.0-4.0 m (7-12 ft) range. Higher waves (> 6.6 m) were also observed on 8% of occasions. The critical limit of 2.0 m wave height was exceeded on 56% of occasions.

In post-monsoon, southerly waves were observed on 29% and southeasterly on 16% of occasions. Northeasterly and easterly wave were also observed on l3% and 10% of occasions. This shows that easterly component is more predominant. Wave heights are generally smaller in post-monsoon season as compared to pre-monsoon season. Wave heights ranging between 4.0-6.6 m (13-20 ft) were experienced on 2% and 25% of occasion in 2.0-4.0 m (7-12 ft) range. Wave height did not exceed 6.6 m (> 20 ft).

In general, south to southwesterly waves were more frequent in pre-monsoon and east to southerly in post-monsoon season. Higher wave heights (*i.e.* exceeding critical limit of 2.0 m) were more frequent (56%) in pre-monsoon as compared to post-monsoon season (27 %). Very high waves (> 6.6 m) were also more frequent in pre-monsoon as compared to post-monsoon season. Higher wave heights reported during the pre-monsoon season under the influence of cyclonic storm may be due to the combined effect of cyclonic circulation and strong Southwest Ocean current. Due to the reversal in the wind and ocean current directions in the post-monsoon season, these factors contribute to suppress the wind and waves generated under the influence of cyclonic storms in the Arabian Sea.

3.2. *Cyclone centered within 500 km in south to west sector from BHA*

Wind and wave roses for cases when cyclones were centered within 500 km in south to west sector from BHA are shown in Fig. 3. In pre-monsoon, winds were more predominant from south to southwest direction. The critical limit of wind speed (> 20 kts) was exceeded frequently (50% of occasions). Wind speeds exceeding 50 kts were also experienced on 9% of occasions. Similarly, waves traveled predominantly from south to southwesterly direction. Wave heights exceeded 2.0 mt (7 ft) more frequently and higher wave heights (>6.6 mt or 20 ft) were also experienced. South to southeasterly winds prevailed during post monsoon. Weaker winds were predominant and wind speeds exceeding 20 kts were experienced only on 15% of occasions. Waves mostly

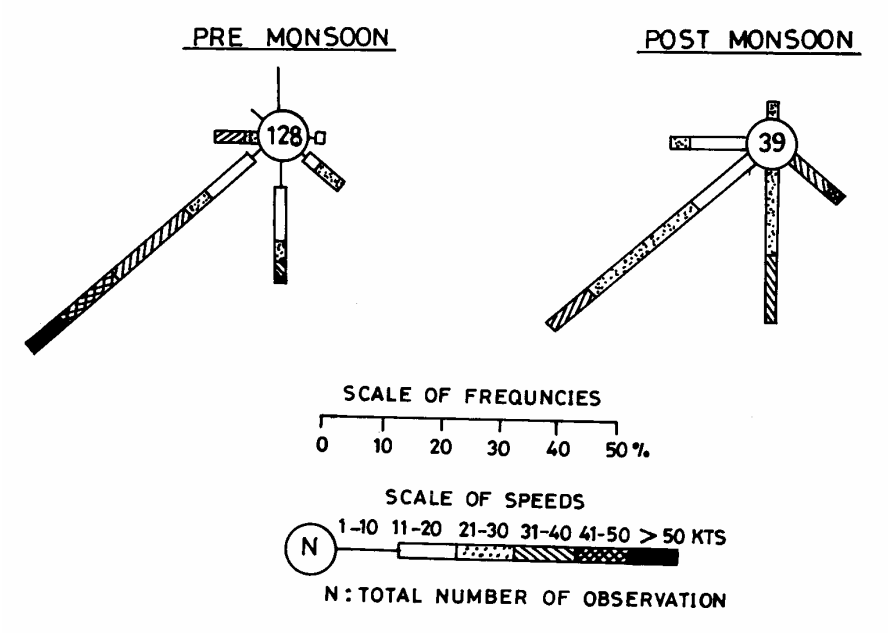

Fig. 4. When cyclone is within 500 km from BHA in west-north sector

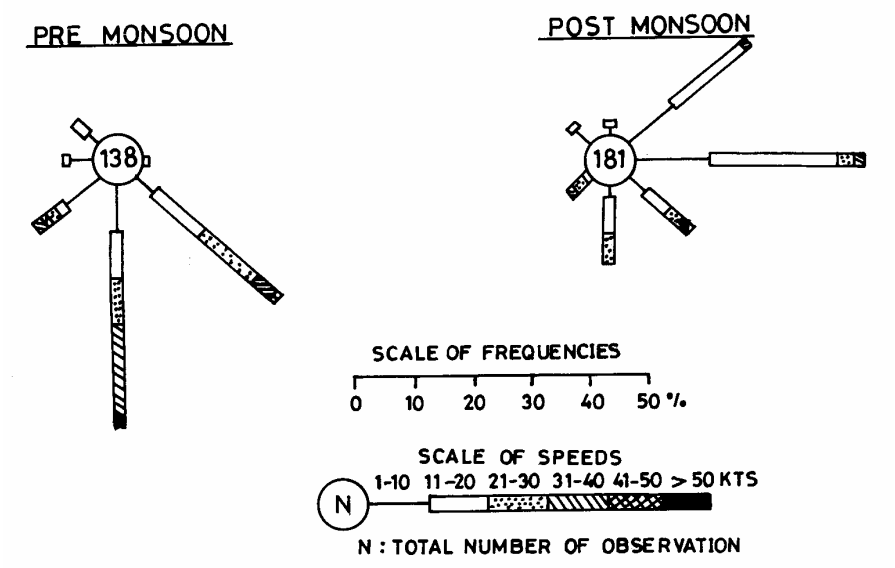

Fig. 5. When cyclone is away by more than 500 km from BHA irrespective of sector

traveled from south to southwesterly directions. Critical wave heights (> 2.0 mt) were experienced on 46% of occasions. In this case, the preferred wind direction was southerly in both the seasons as compared to the general case where southwesterly and southerly directions were preferred in the pre and post-monsoon respectively. Although the frequency distribution of wind speeds between this case and general case showed similarities, the frequency of wind speeds above 40 kts were more in the former. During pre-monsoon, the preferred wave

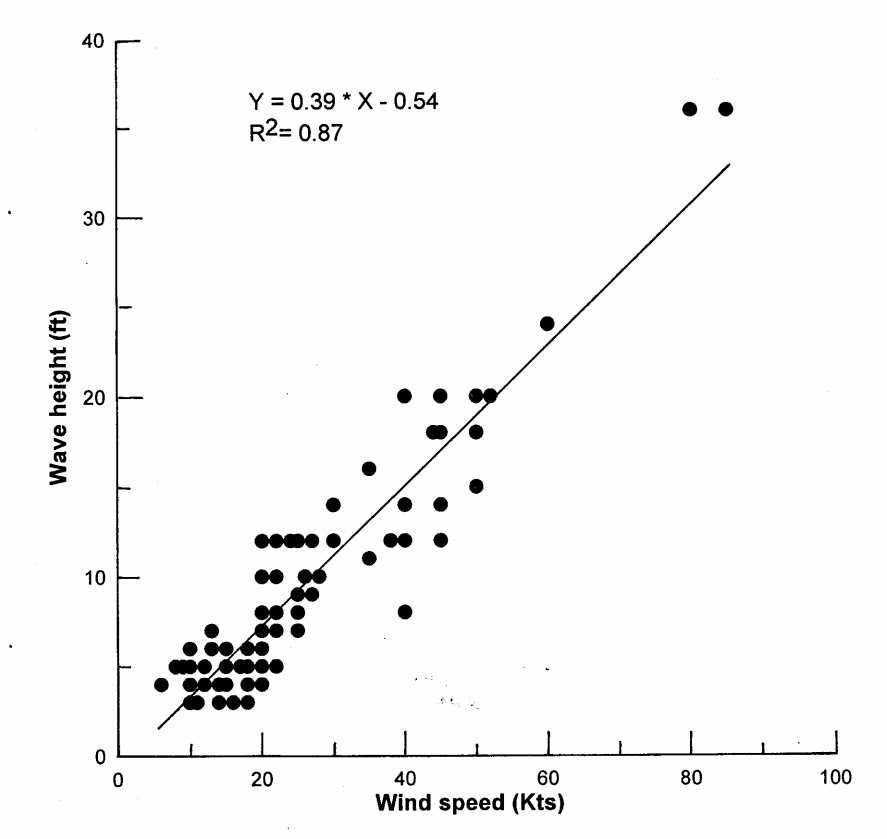

Fig. 6. Relation between maximum wind speed and wave heights

directions were southwesterly for both cases. However, in this case southerly wave directions during post-monsoon were predominant. On 75 % of occasions wave heights exceeded 2.0 mt in this case as compared to the general case where this was only 56%.

3.3. *Cyclone centered within 500 km from BHA in west to north sector*

Wind and wave roses for cases when cyclones were centered within 500 km from BHA in west to north sector are shown in Fig. 4. In pre-monsoon, southwesterly winds prevailed with wind speeds exceeding 20 kts occurring on 51% of occasions. Very strong winds (>50 kts) were observed on only 8% of occasions. Southwesterly waves were more frequent with wave height exceeding 2.0 mt. on 68% of occasions. In post-monsoon, south to southwesterly winds were more frequent and wind speed exceeded critical limit on 72% of occasions. Waves were also prominent from southwest direction and critical limit was exceeded on 75% of occasions. Wind and wave pattern in this case is quite similar to the general case except that in the latter case a prominent easterly component was observed.

3.4. *Cyclone centered away from BHA by more than 500 km*

Wind and wave roses for this case are shown in Fig. 5. In pre-monsoon, southeast to southerly winds with speeds exceeding 20 kts were more frequent. South to southwesterly waves with height exceeding 2 mt were prominent. However, stronger winds (>50 kts) were observed rarely. In post-monsoon northeast to easterly winds were more frequent. Wind speed exceeded critical limit on 16% of the occasions, whereas weaker winds (< 20 kts) were more frequent. Waves traveled from a wide range of directions mainly from northeast to south. Wave height exceeded critical limit on 25 % of the occasions, but smaller wave heights (< 2.0 mt) were more frequent. In this case, wind and wave patterns are quite similar to general case, except that the direction of wind

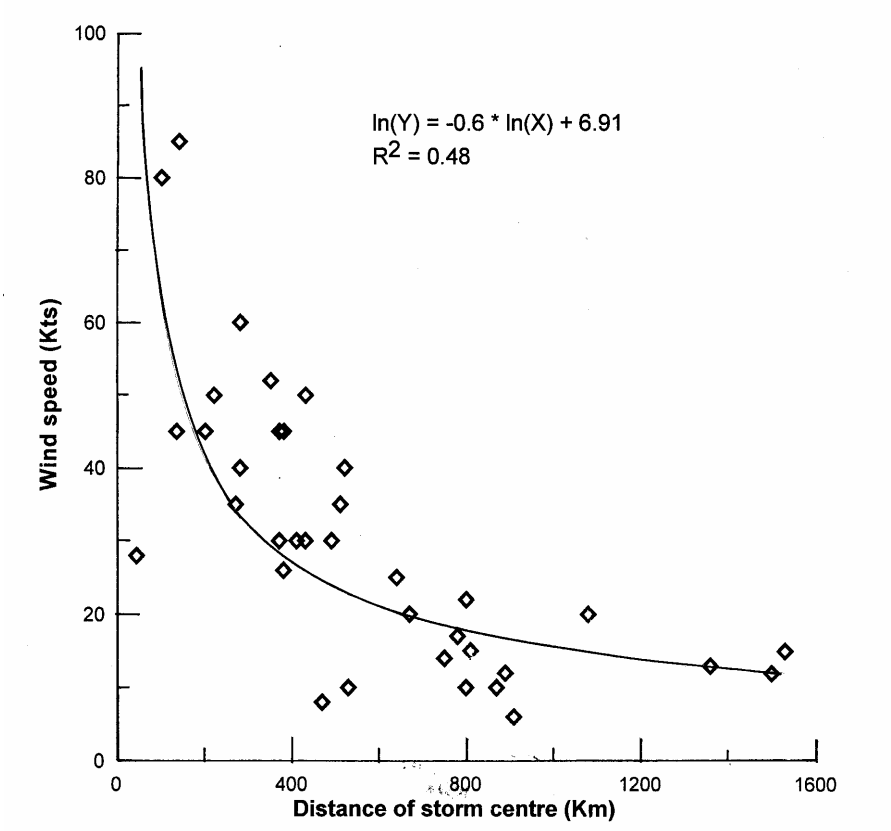

Fig. 7. Relation between distance of the storm centre and wind speed during pre-monsoon

and wave in general case differs slightly with a prominence of westerly component in wind and southerly in waves.

3.5. *A case of low-pressure area/depression centered within 400 km in southwest direction from BHA*

A low-pressure area formed in the Arabian Sea very close to BHA on 12 October 1995 and became depression on 13 October 95. Since this system lay very close to BHA, a separate analysis has been carried out. Mainly easterly winds were experienced and wind speeds ranging between 11-20 kts were observed. Wind speeds rarely exceeded 20 kts. Waves were prominent from east to southeast direction with smaller wave heights (< 2.0 m). Wave heights exceeded the critical limit of 2.0 m on few occasions.

Thus, under such situations, easterly winds with less than 20 kts were more frequent. Similarly, waves from east to southeast direction with smaller wave height can be expected more frequently. As compared to the general case when the cyclone was in the vicinity, in this case critical wind and wave values are surpassed rarely.

4.0. *Empirical relationships*

To evolve more objective methods for estimating wave heights, it is useful to translate climatological information presented in the preceding sections into empirical relations. Comparison of results for the different categories of storm locations with generalized case including all storms formed over the Arabian Sea illustrates the uniformity in the wind direction and speeds that influenced the BHA. Therefore, the generalized case can be considered to represent all situations, and it can be used to characterize the influence of the Arabian Sea cyclonic disturbances on BHA. Accordingly, the generalized situations including all the cyclonic disturbances were used in the analysis for deriving wind-wave and storm-location and wind relationships discussed below.

4.1. *Wind-wave*

Fig. 6 is a plot between wind speeds and wave height. As wind increases, wave height increases linearly

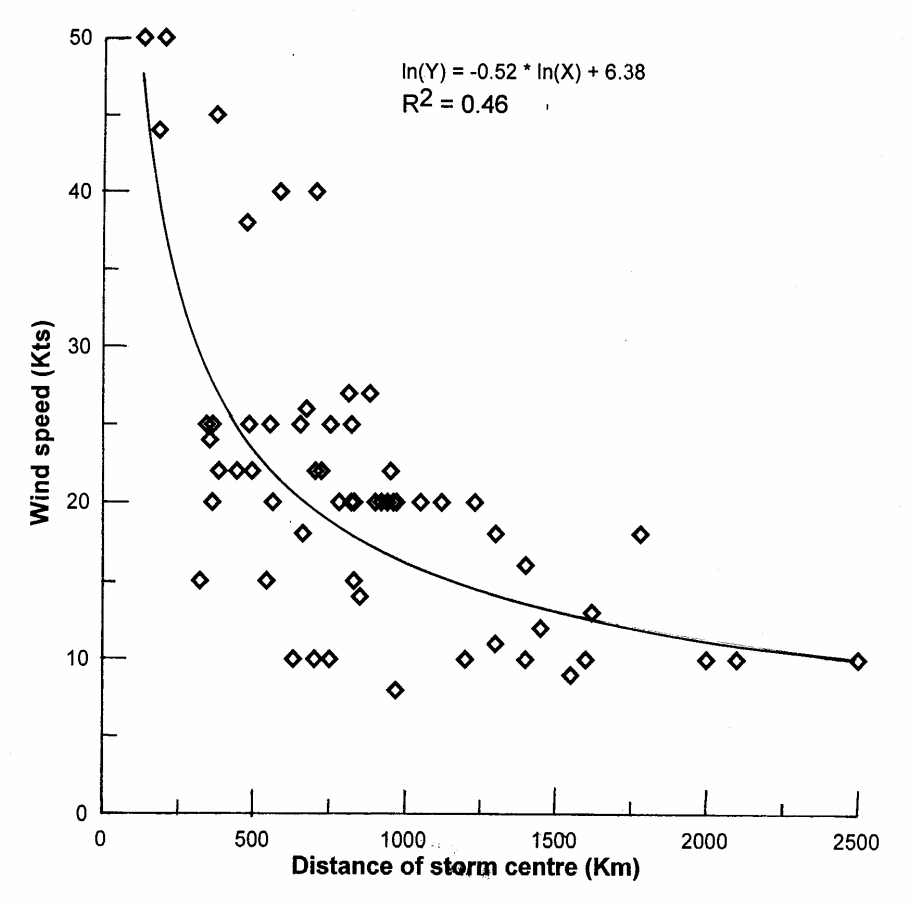

Fig. 8. Relation between distance of the storm centre and wind speed during post-monsoon

and the following equation can be used to represent this relationship :

$$Y = 0.39\,X - 0.54$$

Where, Y is the wave height in feet and X is the wind speed in knots.

The R^2 (co-efficient of determination) value for the above fit is 0.87. Shyamala and Iyer (1989) have also worked out empirical relations between wind speed and wave heights at BHA using 1976-85 data for the months May to October and found linear relations to hold good. Their study was however confined to non-cyclonic conditions on the account of complexity of the situation. The present analysis indicates that despite the complexities some meaningful relations are possible, and could serve as useful tools at critical forecasting situations for BHA. Rarity in cyclonic disturbances moving very close to BHA enables this result. Past records (1971-90) show only a single instance on 2 June 1976 of a cyclonic storm centered, within about 100 km of BHA [India Meteorological Department (1996), Storm tracks]. So, during occasions of cyclonic disturbances in the Arabian Sea, forecaster is presented with a situation where the storm is located at a distance with enough fetch allowing a linear treatment.

4.2. *Wind speed and distance of storm*

It has been also attempted to formulate a relationship between location of the storm center with respect to BHA and wind speed.

Fig. 7 and Fig. 8 shows the curve between maximum wind speed and distance of the storm centre from BHA during pre monsoon season. Logarithmic relationship yields a best fit between wind speed and distance of the storm centre during pre monsoon as well as post-monsoon seasons.

For the pre-monsoon season, the logarithmic fit is given by the equation:

$$\ln(Y) = -0.6*\ln(X)+6.91$$

where Y is the wind speed in knots and X is the distance of the storm centre from BHA in km and the R^2 value is 0.48.

Similarly, in post-monsoon, wind speeds increases logarithmically with respect to the distance of the cyclone given by the equation :

$$\ln(Y) = -0.52*\ln(X)+6.38$$

where Y is the wind speed in knots and X is the distance of the storm centre from BHA in km. R^2 value for this relation is 0.46.

5. Conclusions

Wind speeds and wave heights reach critical limits for offshore operations in the BHA under the influence of cyclonic storms in the Arabian Sea during both pre-monsoon and post-monsoon seasons. Analysis of observations during l990-99 indicates that higher winds and waves are likely to be encountered in the pre monsoon as compared to the post monsoon season. Analysis based on different categories of storm locations shows a large degree of commonality.

Since Arabian Sea cyclonic storms generally occur south of BHA the prevailing wind/wave directions are from the southern quadrants. There is however a tendency for a more westerly component during pre-monsoon and easterly component during the post-monsoon season.

It is possible to workout objective linear relationships between wind speeds and wave heights over BHA, and logarithmic relationship between wind speeds and distance of the storm. These relationships however need further validation under cyclone situations before their implementation on operational basis.

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References

Bhan, S.C., Roy, Bhowmik, S.K. and Sharma, R.V., 1994, "An objective technique for forecasting wind speed over BHA", *Mausam*, **45**, 3, 271-274.

Bhandari, L. L., 1980, "Meteorological requirements for offshore oil exploration", *Vayu Mandal*, **10**, 7-12.

India Meteorological Department, 1979, "Tracks of storms and depression in Bay of Bengal and the Arabian Sea during 1870-1970", I.M.D., New Delhi.

India Meteorological Department, 1996, "Tracks of storms and depression in Bay of Bengal and the Arabian sea during 1971-1990". I.M D., New Delhi.

Mukherjee, A. K. and Sivaramakrishnan, T. R., 1980, "Swells observations on Soviet research ships during Monsoon Experiment (Monex) – 1977 – part II; Arabian sea", *Mausam*, **31**, 3, 447-448.

Mukherjee, A. K. and Sivaramakrishnan, T. R., 1982, "Waves over the Arabian Sea during southwest monsoon", *Mausam*, **31**, 1, 59-64.

Shyamala, B. and lyer, B. G., 1989, "An empirical model for wave field in Bombay High Area", *Mausam*, **40**, 2, 185-191.

Sivaramakrishnan, T. R., 1984, "Wave generation due to monsoon winds in Arabian Sea", *Mausam*, **35**, 1, 239-240.

Thiruvengadathan, A., Padval, S.V. and Singh, R.S., 1984, "Swell over the Arabian Sea during the months, May, June and July", *Mausam*, **35**, 1, 91-98.

Thiruvengadathan, A., 1984, "Waves in the Arabian Sea and the Bay of Bengal during monsoon season", *Mausam*, **35**, 1, 103-106.