

Geosat Altimeter Derived Sea Surface Wind Speeds and Significant Wave Heights for the North Indian Ocean and their Comparison with *in situ* Data

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ABSTRACT

Geosat altimeter data for the period November 1986–October 1987 over the north Indian Ocean have been processed to retrieve wind speeds and significant wave heights. Smoothed Brown algorithm is used to retrieve wind speeds from back-scattering coefficients. From the retrieved wind speeds and significant wave heights, minimum significant swell heights are computed. Three major checks were carried out to prove the accuracy of the data for further analysis. Results are presented in the form of colour coded maps, showing the distribution of mean monthly values of wind and wave parameters over 2.5° square grids. Altimeter derived wind and wave parameters are compared with (i) winds and waves obtained through ships of opportunity and documented in Indian Daily Weather Reports (IDWR), and (ii) waves measured through shipborne wave recorders (SWR) and wave rider buoys (WRB). As data collection through SWR or WRB was not planned originally for comparing with altimeter data, very few altimeter and *in situ* points coincide in time and space frames. Hence, weightage function was applied to altimeter data to get coincident points. The correlation coefficient between wind speed is 0.64 and that for significant wave height, 0.49. However, comparison of monthly averages of Geosat wind speeds and significant wave heights with those of IDWR values over 2.5° square grids shows good agreement. As expected, significant wave heights and wind speeds are higher during monsoon season than during non-monsoon season. Variability of wind and wave parameters during different seasons is clearly seen in the altimeter data.

INTRODUCTION

Paucity of ocean wave data has many times been a limitation for effective utilization and management of coastal and offshore resources in India. Though our research vessels are continuously cruising in the seas around India, it is not possible to achieve a high density data coverage in space and time. Wave rider or directional wave track buoys are capable of providing continuous data, but at a few specified points only. Remote sensing techniques have proved to be worthy partners of *in situ* data collection methods, but to make them mutually compatible, a number of research exercises (viz. retrieval of the parameter, its validation with *in situ* data, spatial and temporal averaging and statistical representation of the data) need to be undertaken.

The radar altimeter flown onboard Geosat satellite in March 1985 was operational for about 5 years and provided very useful global data for obtaining information on ocean surface winds and waves besides sea surface elevation. For this work, Geosat altimeter data for the period November 1986 - October 1987 over north Indian Ocean (lat. 10° S- 25° N; long. 50° - 100° E) has been processed to retrieve wind speeds and significant wave heights. The parameters are averaged over 2.5° square grids. The results of this work are presented mainly in the form of colour grid maps. Geosat derived wind and wave parameters are compared with *in situ* data obtained from Indian Daily Weather Reports (IDWR), shipborne wave recorders (SWR) and wave rider buoys (WRB).

MATERIALS AND METHODS

Geosat altimeter data sets

Basically, a radar altimeter transmits a narrow pulse of electromagnetic radiation and measures the time delay of the return pulse back-scattered from the sea surface. The transmitted pulse is reshaped by scattering at the sea surface and provides additional information on the sea surface conditions. The return pulse is processed onboard and parameters such as significant wave height, back-scattering coefficient and geoid height are available as finished products. Wind speed is computed from the back-scattering coefficient and the significant wave height from the shape of the return pulse.

Experience with Geos-3 and Seasat in the 1970's demonstrated enormous potential of altimetry for oceanographic studies, but neither mission provided a data set that was both long term and global in coverage like Geosat. Since November 1986, the Geosat was manoeuvred into 17.05 day repeat cycle and the mission is known as exact repeat mission (ERM).

The following checks were carried out in the original geophysical data records (GDR) before retrieving the wind and wave parameters: (i) Flagging out the data over land. (ii) Ensuring that the altimeter footprint circles are at least 25 km (i.e., two resolution circles) away from the coastline. For this purpose, the land contour

of the study area was digitized with an accuracy of 25 km. Then a land exclusive grid contour was created and latitude and longitude of each data point were checked to find out whether the data point was within the permissible ocean area or not. (iii) Ensuring that the standard deviations of the data used are < 25% of the parameter values. Standard deviation of significant wave height is given in the source tapes; since the same is not given for back-scattering coefficient, standard deviation of automatic gain control (AGC), from which back-scattering coefficient is deduced, is used in the check.

Techniques for retrieval of wind and wave parameters

Wind speed (W) — Various theoretical and empirical models are available to estimate wind speed from radar back-scattering coefficient (σ°). The relationship between σ° and W exists mainly because of variation in the slope distribution caused by surface wind speed. The most commonly used theoretical model is that provided by Barrick [2].

$$\sigma^\circ = (1/S^2) |R(\theta)|^2 \sec^4 \theta \exp(-\tan^2 \theta / S^2)$$

where $R\theta$ is nadir reflection coefficient; and S , surface slope variance. Algorithms of empirical models are developed mainly with buoy and spaceborne altimeter data (viz., Geos-3 and Seasat). Brown algorithm [3] was developed with buoy and Geos-3 altimeter data over north Atlantic and Pacific Oceans. Chelton and McCabe [4] pointed out that Brown algorithm produced a multimodel wind distribution due to discontinuity in the algorithm and developed their algorithm with wind speed values obtained from Seasat altimeter and vertically polarised scatterometer returns. Chelton and Wentz [5] further improved the Chelton-McCabe algorithm by modifying the averaging and comparing procedures. Goldhirsh and Dobson [8] fitted a smooth curve to Brown's Geos-3 and buoy data and developed a fifth degree polynomial:

$$W = \sum_{n=0}^5 a_n (\sigma^\circ)^n, \quad 5.4 \leq \sigma^\circ \leq 15$$

where $a_0 = -15.383$; $a_1 = 16.077$; $a_2 = -2.305$
 $a_3 = 0.09896$; $a_4 = 0.00018$; $a_5 = -0.00006414$.

For radar cross-section (RCS) values < 5.4 db

$$W = 1.04 \sigma^\circ + 14.04203$$

For RCS values > 15 db

$$W = 0.01266 \sigma^\circ + 1.381207$$

Analysis with the data of Geosat and NDBC buoys has shown that the smoothed Brown algorithm has the least rms error of 1.8 m/s [7]. In this work, smoothed Brown algorithm is used. Significant wave height (SWH) was estimated from the slope of the leading edge of the return wave form. This parameter is available as a finished product in Geosat GDR.

Minimum significant swell height (MSSH) was estimated from the significant wave height (SWH) and wind speed (W) based on energy balance equation and Pierson-Moskowitz spectra, using the following relationship [11]:

$$\text{MSSH} = \sqrt{E_s}$$

$$\begin{aligned} \text{where } E_s &= E_{\text{alt}} - E_{\text{fd}} \\ E_{\text{alt}} &= 0.0625 (\text{SWH})^2 \\ E_{\text{fd}} &= 0.0625 (\text{SWH})_{\text{fd}}^2 \\ \text{SWH}_{\text{fd}} &= 0.0258 (W_{10})^2 \end{aligned}$$

E_s is the estimate of swell energy in the limiting case of a fully developed sea and E_{alt} is the energy estimated from the altimetric measurement of SWH.

Map generation — Utilizing the CALCOMP plotter, continental boundaries of India and neighbouring countries for the area of interest have been digitized and stored. Various softwares have been developed [13] to enter the values of wind speed, significant wave height, minimum significant swell height, their corresponding standard deviations and the total number of observations in 2.5° square grids and to mask the land portion. Monthly averages and standard deviations of each parameter were entered in their respective grids. Thus, for each parameter, 12 maps were generated. A typical map of significant wave height for the month of June 1987 is shown in Fig.1. The first value in the grid is SWH and the second, its standard deviation.

A set of computer programs has been developed [1] to present the wind and wave parameters in colour grid images using the image processing system. These programs are used (i) to convert latitude and longitude values as points on an image of 1024 pixels/1024 lines, (ii) to convert numerical data into images, (iii) to overlay the images on a map showing the Indian sub-continent, Arabian Sea, Bay of Bengal and north Indian Ocean extending from 10° S to 25° N and 50° to 100° E, and (iv) to mask the land portion from sea. The colour band follows the VIBGYOR pattern, indicating violet for the lowest value and red for the highest value of the parameter. At the bottom of each colour map, a gray value code is created to define the value of the parameter. Thus, 12 images are created for each parameter. Though colouring is extended up to the coastline, Geosat values within 25 km from the coast have not been considered (to avoid land contamination in the data). Typical colour maps, showing the distribution of wind speed, SWH and minimum significant swell height for June 1987 are presented in Fig. 2.

RESULTS AND DISCUSSION

Comparison of SWH and W with *in situ* data

The following types of comparison are normally made between satellite derived and *in situ* measured geophysical parameters: (i) point comparison - within spatial and temporal separations over which the parameter is assumed to

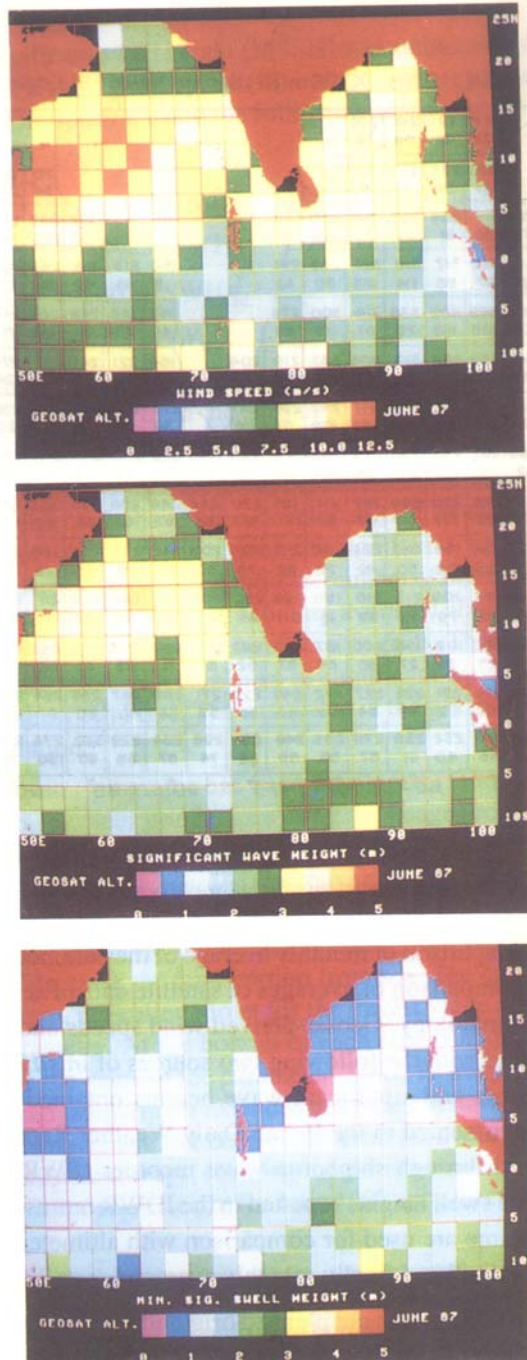


Fig.2 — Typical colour maps showing the distribution of wind speed, SWH and MSSH for June 1987

data points are compared with monthly averages of altimeter values over 2.5° grids. The results are presented in Table 1.

As limited buoy data are available, IDWR data within 1.5° of satellite passes are used for comparison. Since ships report data every 6 hours, time separation is 3 hours. To compare IDWR data with altimeter data for a spatial separation of 1.5°, the following technique is employed: satellite passes over the area of interest are drawn. A circle of radius 1.5° with ship as the centre cuts the Geosat passes at two points and all the altimeter data between these two points are considered. The following weightage function (W_i) is applied to each significant wave height and wind speed value:

$$W_i = (1.0 - R_i / \sum R_{ij}) / (n - 1)$$

where n is the number of points; and R_i , distance between i -th point on satellite pass and the ship. The weighted observations are averaged to yield the final value of the parameter. These values are compared with the corresponding IDWR data. This procedure has yielded only 41 significant wave height pairs and 59 wind speed pairs. The correlation coefficient of wind speed is 0.64 (slope of the best line is 0.89) and that of significant wave height, 0.49 (slope of the best line is 0.54). The poor correlation of wave height is due to the very nature of visual observations.

Further, monthly averages of wind speeds and significant wave heights over 2.5° square grids are compared with the corresponding altimeter values. This resulted in a large number of points. For comparison purpose, wind speed and significant wave height for January, July and October, representing data for different seasons are clubbed together and plotted (Figs 5, 6). These figures show good comparison for monthly averaged values. Though this sort of comparison is not ideal for validation purpose, the results will be useful in coastal/offshore engineering applications.

Table 1 — Monthly Averages of *in situ* and Geosat Derived Waves and Winds
[Values within parentheses represent monthly average of Geosat derived parameters]

Month	Location		Sig. wave height (m)	Wind speed (m/s)
	lat.	long.		
Nov. 1986	15°00'N	73° 00'E	1.10 (0.98)	— (4.8)
Dec. 1986	09°55'N	75° 45'E	0.66 (0.91)	2.06 (3.6)
Mar. 1987	16°29'N	84° 35'E	0.96 (0.54)	5.54 (5.9)
May 1987	12° 29'N	92° 32'E	0.63 (0.87)	3.12 (3.5)
June 1987	9° 50'N	75° 49'E	2.36 (2.40)	10.40 (7.8)

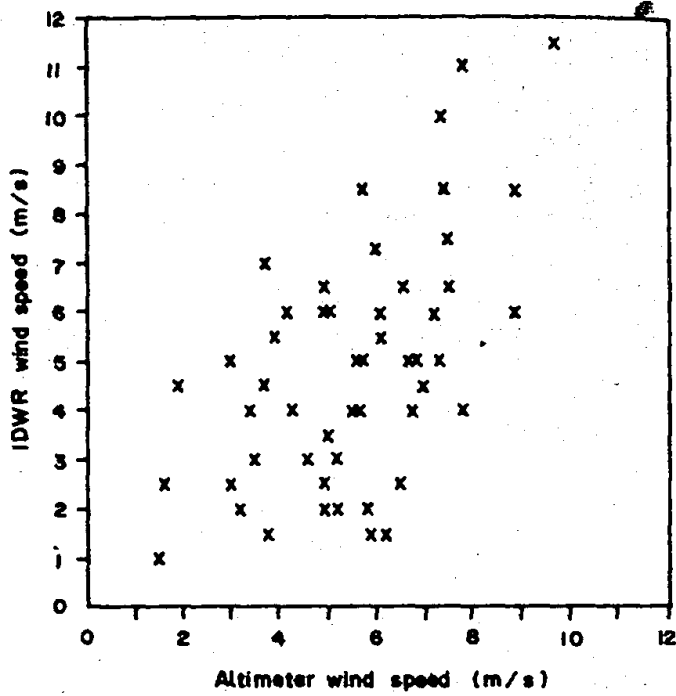


Fig.3 — Comparison of wind speed obtained through IDWR and Geosat altimeter (no. of points = 59)

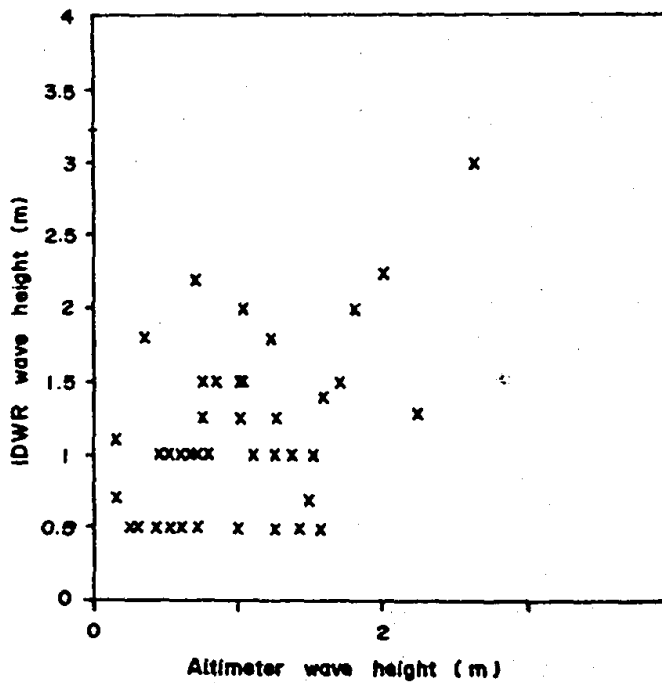


Fig.4 — Comparison of significant wave heights obtained through IDWR and Geosat altimeter (no. of points = 41)

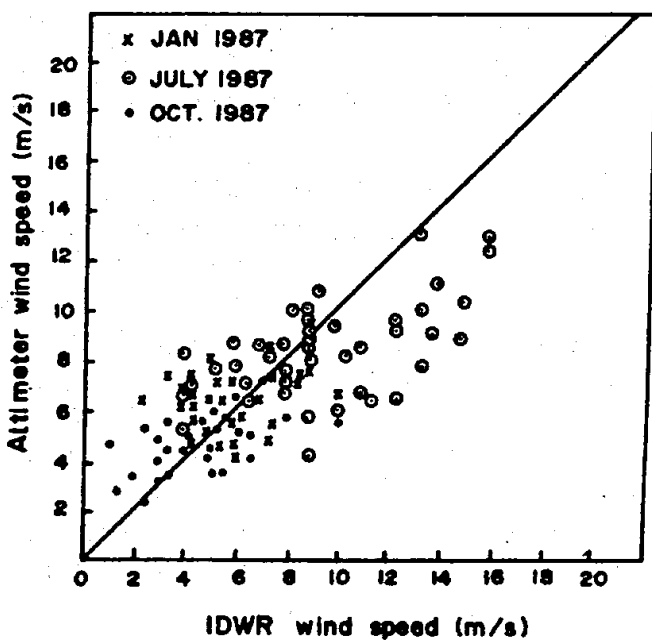


Fig.5 — Comparison of monthly averages of *in situ* and altimeter wind speed

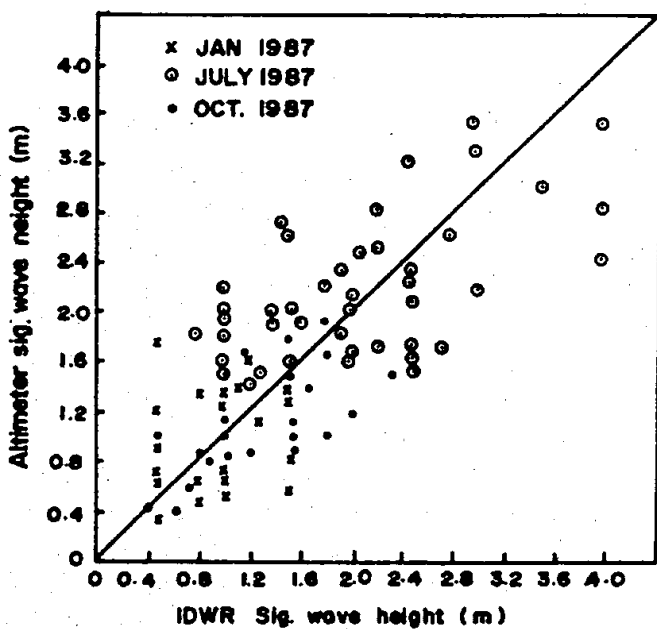


Fig.6 — Comparison of monthly averages of *in situ* and altimeter significant wave height

Wind and wave pattern in the north Indian Ocean

The results of the work are presented in the form of mean monthly maps of surface wind speed, significant wave height and minimum significant swell height over 2.5° square grids within the region bounded by 10° S to 25° N and 50° to 100° E, covering north Indian Ocean comprising Arabian Sea and Bay of Bengal [15].

The minimum values of surface wind speed range between 1.5 and 2.4 m/s. The maximum wind speed values encountered are within the range of 8.1-14.6 m/s. The maximum wind speeds are mostly found in the western Arabian Sea during southwest monsoon months. From May onwards, winds of the order of 5-7 m/s are seen north of Equator and off Somalia. This agrees with values reported in the climate atlas of Hastenrath and Lamb [10]. Strong winds (11-12.5 m/s) are encountered during June-July in Arabian Sea (5° - 15° N; 50° - 65° E). In August, the wind speeds begin to subside. As expected, during December- January, winds are stronger in Bay of Bengal (\sim 8 m/s). Southwest monsoon features (strong winds of the order of 6-10 m/s) are also seen in the Bay of Bengal. The strong winds (\sim 12 m/s) encountered in the north Bay of Bengal during February are attributed to the cyclone which occurred during 30 January - 5 February 1987 [6].

Significant wave height varies between 0.05 and 4.07 m. The lowest value of 0.05 m encountered in a grid may be due to land contamination in the data. Otherwise, the minimum value of SWH is 0.21 m. Since the measurement goal of significant wave height of Geosat altimeter was set at 0.5 m, all values below 0.5 m should be used with caution. As expected, significant wave heights are higher (2-4m) during monsoon months. In June, off Somalia and in central Arabian Sea, SWH values are higher, probably due to the presence of high swells. During non-monsoon months, relatively lower wave heights persist in the entire north Indian Ocean. This agrees with the general wave climatology of this region [9,14].

Swells up to 3 m are present in the northeast Arabian Sea. Swell components in the rest of the Arabian Sea have the constant magnitude of 1-1.5 m and do not clearly show the direction of propagation due to the absence of a marked gradient in their magnitudes. The swell condition during December-March appears to be stable and has low values (1m) both in the Arabian Sea and the Bay of Bengal, and April onwards swell heights are increasing. In the premonsoon month of May, swell heights are of the order of 2-2.5 m and in July almost everywhere swells are present with a higher magnitude. Referring to concurrent wind and wave field patterns, it is evident that swells have lagged the wave patterns, but have a similar orientation. Band-like patterns of swells with larger heights are seen to proceed from the south of Equator to north Indian Ocean during southwest monsoon period. A similar phenomenon has been reported by Mukherjee and Sivaramakrishnan [12] over Arabian Sea using *in situ* data. From August to November, the band-like patterns get diminished and gradually diffused with lower values, leading finally to a stable value (\sim 1.5 m).

CONCLUSION

Using the improved algorithm, wind speed and swell heights have been retrieved from the raw altimeter data. Several softwares have been developed to generate maps of the wind and wave parameters. Altimeter results are compared with available *in situ* data. As *in situ* data collection was not planned originally during satellite overpasses, point to point comparison with altimeter data could not be carried out. However, monthly mean of wind speed in 2.5° square grids matches with the IDWR monthly mean. Overall wind patterns are in agreement with the known climatology of the area of interest. Matching of wave climatology is not so striking; this may be due to visual nature of wave observations. This exercise could be further extended to generate a comprehensive wind and wave climatology with the entire Geosat, ERS-1 and future satellite data.

ACKNOWLEDGEMENT

The authors express their sincere thanks to the Director of NIO and SAC for providing facilities at their respective organizations to carry out this work.

REFERENCES

1. Almeida, A.M., K. Santanam, R. Vaithyanathan and P. Vethamony. 1990. A software package for creating continental outline and colour grid maps for oceanographic and meteorological atlases, Technical Report No. NIO/TR-18/90, NIO., Goa, India.
2. Barrick, D.E. 1974. Wind dependence of quasi-specular microwave sea scatter, *IEEE Trans. Antenna & Propag.* AP 22: 135-136.
3. Brown, G.S., M.R. Stanley and N.A. Roy. 1981. The wind speed measurement capability of spaceborne radar altimeters, *IEEE J. Oceanic. Engng.* 6: 59.
4. Chelton, D.B. and P.J. McCabe. 1985. A review of satellite altimeter measurement of sea surface wind speed with a proposed algorithm, *J. Geophys. Res.* 90: 4704-4720.
5. Chelton, D.B. and F.J. Wentz. 1986. Further development of an improved altimeter wind speed algorithm, *J. Geophys. Res.* 91: 14250-14260.
6. Das N., D.S. Desai and N.C. Biswas. 1989. Cyclones and depressions over the Indian seas and Indian subcontinent during 1987, *Mausam*, 40: 1-12.
7. Dobson, E.B., F. Monaldó, J. Godhirsh and J. Wilkerson. 1987. Validation of Geosat altimeter-derived wind speeds and significant wave heights using buoy data, Johns Hopkins APL Technical Digest, 8(2): 222-233.
8. Godhirsh, J. and G.B. Dobson. 1985. A recommended algorithm for the determination of ocean surface wind speed using a satellite-borne radar altimeter, JHU/APL SIR85U-005.
9. Gorshkov, S.G. (Ed.). 1978. World Ocean Atlas, Vol. 2 (Atlantic & Indian Oceans), Pergamon Press.
10. Hastenrath, S. and P.J. Lamb. 1979. Climate Atlas of the Indian Ocean, Part I, The University of Wisconsin Press.
11. Mognard, N.M., W.J. Campbell and C. Brossier. 1984. World ocean mean monthly waves, swell, and surface winds for July through October 1978 from SEASAT radar altimeter data, *Mar. Geod.* 8: 159-181.
12. Mukherjee, A.K. and T.R. Sivaramakrishnan. 1980. Swell observations on Soviet research vessels during monsoon experiment (MONEX) 1977 - Part II: Arabian Sea, *Mausam*, 33(3): 447-448.

13. **Raj Kumar, B.S. Gohil, R.M. Gairola, R.V.L.N. Prasad and A. Sarkar.** 1991. A software manual of GEOSAT-derived wind and wave parameters over seas around India, SAC Report No. SAC/RSA/RSAG/MAN/1/91.
14. **Ramage, C.S.** 1984. Climate of the Indian Ocean North of 35°S. *Climate of the Oceans*, (ed.) H. Van Loon, Elsevier: 603-658.
15. **Anon.** 1990. Winds and waves over the north Indian Ocean derived from Geosat altimeter data. Sci. Report, ISRO-NNRMS-SR-40-90.