Development of the wave spectrum of the northern region of the Bay of Bengal based on Indian National Centre for Ocean Information Services (INCOIS) moored buoy data

M Mansur[1*], **F B Enam**[1] and **M S Baree**[1]
[1]Department of Naval Architecture and Marine Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh
[*]Corresponding e-mail: maqsoodmansur@gmail.com

Abstract: *The wave spectrum of the northern region of the Bay of Bengal is developed and analyzed. A meticulous analysis shows variations of the wave spectrum of this region in the four meteorological seasons namely spring (March, April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February). Real time wave data have been collected from a moored buoy of Indian National Centre for Ocean Information Service (INCOIS) located at 89.675° E longitude and 18.191° N latitude. Varying two-parameter (mean wave period and significant wave height) wave spectra for the four seasons are obtained and formulae for all the four spectra are derived. The adequacy of the different spectra is indicated by comparing with different wave spectra of known formulations.*

Keywords: *Wave spectrum, Bay of Bengal, meteorological seasons, significant wave height, mean wave period.*

INTRODUCTION

Waves in the sea or ocean, generated by wind, generally consist of locally generated waves and the swells propagating from the far-flung locations[1]. These waves are not just simple sinusoids. The surface appears to be composed of random waves of various height, lengths, periods and shape. This randomness results in limited predictability. They can be described as a stochastic process[2]. As such we cannot describe this surface very easily. However, with some simplifications, we can come close to describing the surface. The simplifications lead to the concept of the spectrum of waves. The spectrum gives the frequency wise distribution of wave energy on the sea surface[3]. Thus we can say that the wave spectrum is an expression for the distribution of energy in the waves. The knowledge of waves and wave spectrum has widespread scientific and practical applications. These range from engineering applications such as the design and operational safety of harbors, ships, and offshore structures to coastal and marine management including, e.g. coastal stability, marine and coastal pollution and marine operations planning[4-6].

However, the Earth's climate is dynamic and varies naturally over a range of time-scales[7]. These variations and trends tend to instigate a number of physical processes culminating a 'herculean' impact on the marine environment. The varying atmospheric and climatic conditions observed in these time-scales or in other words, in different seasons stimulate variations in the spectral characteristics of the sea or ocean waves[8-26]. The monsoons of the Indian Ocean are the beau ideals of particularly strong ocean– atmosphere interaction. The large-scale wind field in the northern Indian Ocean reverses between summer and winter, leading to changes in the waves[11]. Hence, it is important to know how the wave spectrum varies with the change in seasons over a period of one year.

Many studies have been conducted in this region regarding this wave spectral characteristics and its variability. Kumar and Nair[11] studied the inter-annual variations in wave spectral characteristics at a location off the central west coast of India. Patra and Bhaskaran[17] tried to find the trends in wind-wave climate over the head Bay of Bengal region and Shanas and Kumar[22], on the other hand, focused on the long-term wind and wave in the central Bay of Bengal and studied its seasonal variability. Jena et al.[23] conducted a study on the seasonal variation in near shore wave characteristics off Cuddalore, southeast coast of Tamil Nadu, India. Potemraet al.[24] researched on the seasonal circulation of the upper ocean in the Bay of Bengal. Cheng et al.[25] studied the intraseasonal variability of sea surface height in the Bay of Bengal. Seasonal and annual variations in the wave climate over the near shore waters off Puduchery, south western Bay of Bengal induced by monsoon and cyclone were studied by Glejin et al.[26]. Chaudhary et al.[27] derived significant wave height in the Bay of Bengal basin of the Indian Ocean near the Indian city of Visakhapatnam for the years 2010–2012. Kumar et al.[28] studied the wave spectral characteristics off Gangavaram, Bay of Bengal. Islam et al.[29] calculated wave energy and analyzed energy fluctuation at various months of different consecutive years in the Bay of Bengal. However, no study has been conducted to develop and analyze the wave spectrum in the northern region of the Bay of Bengal for the different seasons. So, a research study is needed in this regard.

Meteorologists and climatologists divide the seasons into four with each having a grouping of three months. Meteorological spring includes March, April, and May; meteorological summer includes June, July, and August; meteorological autumn or fall includes September, October, and November; and meteorological winter includes December, January, and February[30]. During these four seasons, various climatic factors vary which ultimately leads to the variations in wave spectra.

A study is carried out from March, 2015 to February, 2016. A location of study is selected where the measured wave data is available. The geographical co-ordinates of the location are 89.675° E longitude and 18.191° N latitude.

The objective of the study is to investigate the characteristics of wave spectrum of northern region of the Bay of Bengal and its seasonal variation and derive formulae for the wave spectra and thus, to have a better understanding of the nature of the waves occurring in the region.

DATA AND METHODOLOGY

Data

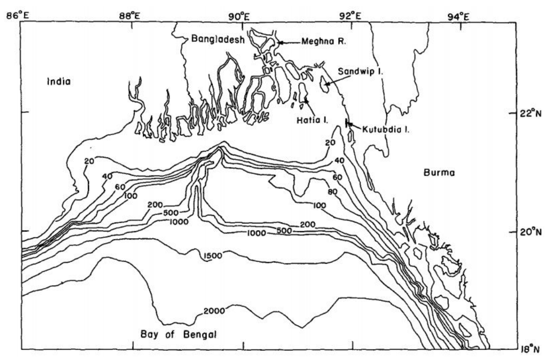

Figure 1: Map of the northern Bay of Bengal[31].

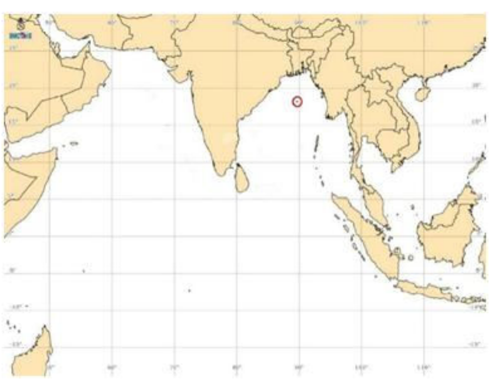

Figure 2: Map showing 'Moored Buoy BD-08'.

The data used in the study were taken from the website of Indian National Centre for Ocean Information Service (INCOIS), covering the period from March, 2015 to February, 2016. The URL link of the website is: http://odis.incois.gov.in/. INCOIS receives voluminous oceanographic data in real time, from a variety of in-situ and remote sensing observing systems. To achieve this purpose INCOIS has installed many buoys. As a part of this, they installed a moored buoy at location 89.675° E longitude and 18.191° N latitude in the Bay of Bengal named 'Moored Buoy BD-08' (red circle in Figure 2). Data of this buoy is used in this study.

Methodology

The wave spectra for each of the seasons were obtained from the data using histogram[32]. It is known that when umpteen sinusoidal waves of disparate wavelengths, heights and periods superpose on each other, irregular wave pattern is developed. This superposition results in an extremely irregular seaway that is never repeated anytime[32]. The wave spectrum of this seaway can be obtained by measuring the total energy content of all the waves present. According to Bhattacharyya[32], the energy of a sinusoidal wave is given by,

$$E_s = \frac{1}{2}\rho g \zeta^2 \tag{1}$$

where, ζ is the amplitude

The total energy is then given by

$$E_T = \frac{1}{2}\rho g(\zeta_1^2 + \zeta_2^2 + ... + \zeta_n^2) \tag{2}$$

where, $\zeta_1, \zeta_2, ..., \zeta_n$ are the amplitudes of the waves

Hence, energy spectrum is the distribution of this total energy according to frequency of waves where the ordinates are obtained by dividing the individual energy content by the bandwidth, which is 0.2 in this study. The energy density or spectral density results when ρg is divided out from the energy, given by,

$$S_w = \frac{1}{2}(\zeta_1^2 + \zeta_2^2 + ... + \zeta_n^2) \tag{3}$$

where, S_w is the energy density

Wave spectrum is the distribution of energy density according to frequency of waves. Mathematically,

$$S_w / \delta w = \frac{1}{2}(\zeta_1^2 + \zeta_2^2 + ... + \zeta_n^2) \tag{4}$$

where, δw is the bandwidth.

The wave spectrum curve can be obtained from these histograms. By averaging, the final wave spectrum results[33]. This method was exercised in the study. The data was processed and computations were done accordingly to obtain wave spectra for all the seasons. The significant wave height and mean time period for each season is also computed. Correction factor for the

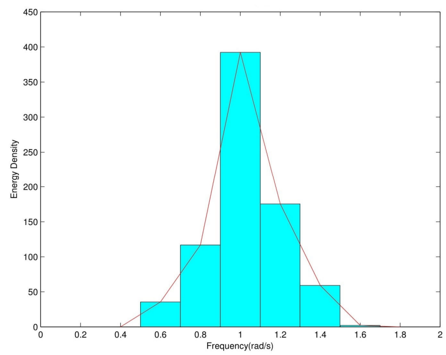

Figure 3: Spring wave spectrum with histogram.

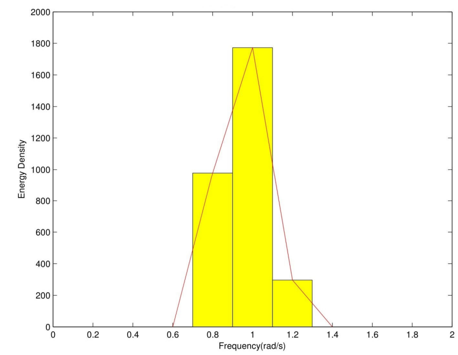

Figure 4: Summer wave spectrum with histogram.

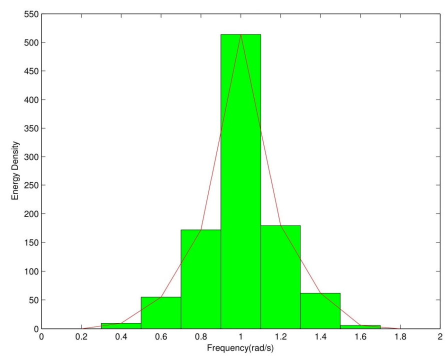

Figure 5: Autumn wave spectrum with histogram.

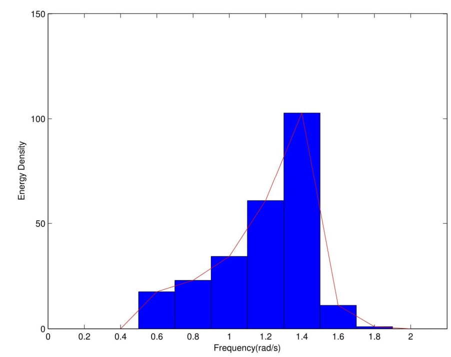

Figure 6: Winter wave spectrum with histogram.

wave spectra are derived showing the deviation from Rayleigh distribution from the equations given below:

$$CF = (1 - ò^2)^{\frac{1}{2}} \quad (5)$$

where, CF is the correction factor and $ò^2$ is the broadness parameter which is given by the expression,

$$ò^2 = \frac{m_0 m_4 - m_2^2}{m_0 m_4} \quad (6)$$

where the moment of the area under the spectrum is

$$m_n = \int_0^{\infty} w^n S_w dw \quad (7)$$

Here, n is any integer and m_n is the nth moment of the area under the spectrum.

Four equations using the parameters significant wave height and mean time period are set describing the spectra of the four seasons, henceforth, showing the seasonal variation. The spectra are compared with different standard wave spectra namely ITTC spectrum[34, 35], JONSWAP spectrum[35, 36], Scott spectrum[35, 37] and Ochi-Hubble bi-modal spectrum[35, 38] measured for respective seasons at this location in order to assess the adequacy of the result obtained.

RESULTS AND DISCUSSIONS

Wave spectra

As per the method outlined in the previous section, histograms and wave spectra for the four seasons were obtained (Fig. 3, Fig. 4, Fig. 5 and Fig. 6).

The final wave spectra were obtained by averaging (Fig. 7, Fig. 8, Fig. 9 and Fig. 10).

Significant wave height and mean wave period

Significant wave height (SWH) and mean wave period for the four seasons were analyzed from the data (Table 1).

Table 1: Significant Wave Height (SWH) and Mean Wave Period.

Season	Significant Wave Height(m)	Mean Wave Period(s)
Spring	1.77	6.40567861
Summer	3.32	6.328103411
Autumn	2.01	6.453918845
Winter	0.99	5.251915237

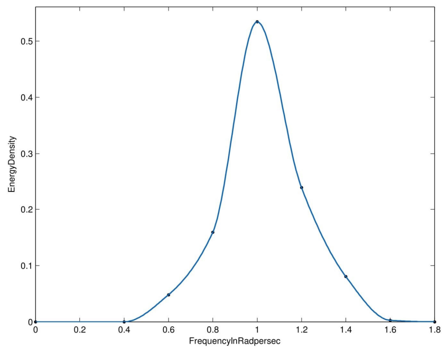

Figure 7: Final spring wave spectrum.

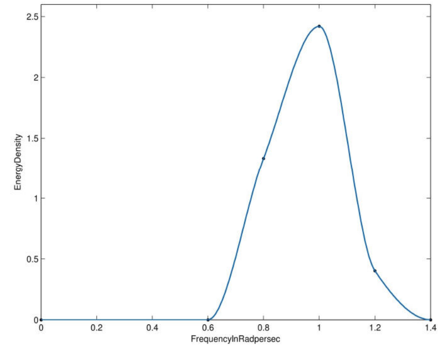

Figure 8: Final summer wave spectrum.

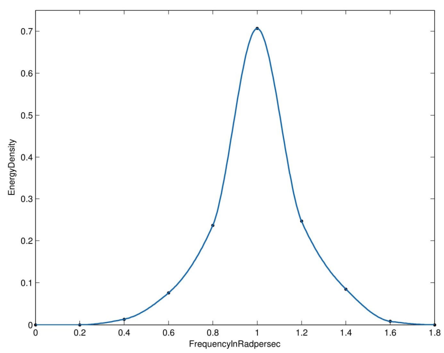

Figure 9: Final autumn wave spectrum.

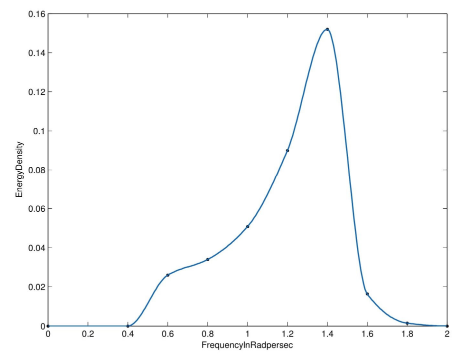

Figure 10: Final winter wave spectrum.

Correction factor

Correction factor of the wave spectra of the four seasons were calculated showing how much the spectra deviates from 'narrow frequency spectrum'[32] (Table 2). The deviation was different for different seasons leading to the seasonal variation of the correction factor as well.

Table 2: Correction Factor (CF).

Season	CF
Spring	0.981772626
Summer	0.930123968
Autumn	0.981771781
Winter	0.891792832

Equations of the wave spectra

Equation was derived for the wave spectra of each season. Significant wave height and mean wave period are the parameters used in the equations.

The spring wave spectral equation of Northern Bay of Bengal is given by,

$$S_w = \frac{a*H_S^3}{g*T_m}*\exp(-\sqrt{\frac{(w-b)^2}{c*(w+d+e*T_m)}}) - f*H_s^2*T_m *\exp(\frac{H_s^2*w^4}{T_m}) \quad (8)$$

where, a = 7.099133; b = 1.027581; c = 0.0108036; d = 0.8876376; e = 0.1518847; f = 5.914×10^{5};

w is the frequency in rad/sec;

g is the acceleration due to gravity in ms^2;

H_s and T_m are significant wave height and mean wave period respectively whose values for spring are 1.77 m and 6.40567861 sec respectively (Table 1).

For summer, the spectral equation is given by,

$$S_w = a*g^2*T_m^5*\exp(-(\frac{w-\frac{b}{T_m}}{c})^2) + d*H_s^2*T_m *\exp(-(\frac{w-\frac{e}{T_m}}{f})^2) \quad (9)$$

where, a = 0.0005708; b = 5.71172; c = 0.0417619; d = 0.7029379; e = 7.191828; f = 0.0289901

g is the acceleration due to gravity in ms^2;

H_s and T_m for summer are 3.32 m and 6.328103411 sec respectively (Table 1).

The wave spectral equation for the autumn season is,

$$S_w = a*g^2*T_m^5*\exp(-(\frac{w-\frac{b}{T_m}}{c})^2)+d*H_s^2*T_m *\exp(-(\frac{w-\frac{e}{T_m}}{f})^2)-\frac{h*H_S^3}{g*T_m}*\exp(\frac{H_S^2*w^4}{T_m}) \quad (10)$$

where, a = 5.548 x 10 ^{5}; b = 6.04062; c = 0.0283126; d = 0.0133533; e = 6.496685; f = 0.3313183; h = 0.0007354;

g is the acceleration due to gravity in ms^2;

H_s and T_m for autumn are 2.01 m and 6.453918845 sec respectively (Table 1).

The equation of the wave spectrum for the winter is,

$$S_w = a*g^2*T_m^5*\exp(-(\frac{w-\frac{b}{T_m}}{c})^2)+d*H_s^2*T_m *\exp(-(\frac{w-\frac{e}{T_m}}{f})^2)-h*g*H_s*T_m^3*\exp(\frac{H_S^2*w^4}{T_m}) \quad (11)$$

where, a = 6.702 x 10 ^{7}; b = 6.934648; c = 0.0901302; d = 0.0098529; e = 5.654206; f = 0:5557179; h= 8.055 x 10 ^{7};

g is the acceleration due to gravity in ms^2;

H_s and T_m for winter are 0.99 m and 5.251915237 sec respectively (Table 1).

Comparison with other known wave spectra

The spectra of the four seasons are analogized to ITTC spectrum, JONSWAP spectrum, Scott spectrum and Ochi-Hubble bi-modal spectrum of respective seasons (Fig. 11, Fig. 12, Fig. 13 and Fig. 14).

It can be seen that the spectra of all the seasons except winter are comparable to the Scott spectrum of the corresponding seasons. The winter spectrum gives a unique representation.

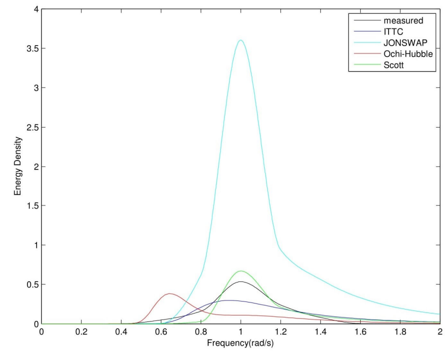

Figure 11: Spring wave spectrum comparison.

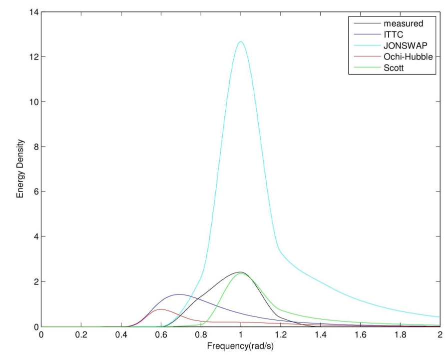

Figure 12: Summer wave spectrum comparison.

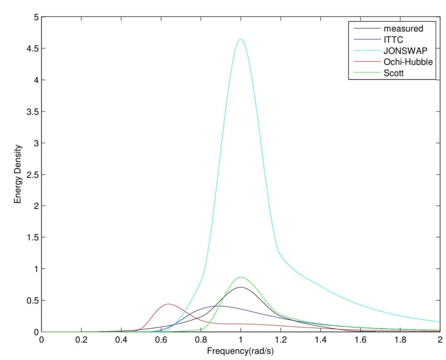

Figure 13: Autumn wave spectrum comparison.

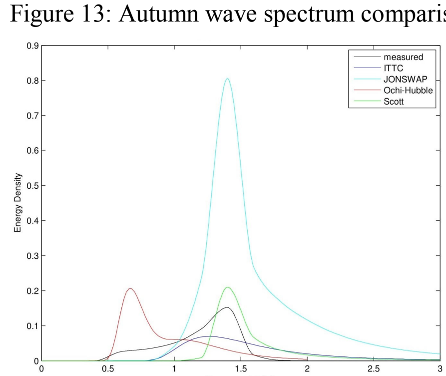

Figure 14: Winter wave spectrum comparison.

Seasonal variations of the wave spectrum and deviation of the measured spectra from other known spectral formulations

The energy content at different frequency bands varied from season to season, thus, showing the state of the sea (according to ITTC recommended procedures and guidelines) at different seasons. Summer showed a rough state (SWH is 3.32 m) and winter showed a slight sea state (SWH is 0.99m). Sea state in both spring and autumn was moderate (SWH is 1.77m and 2.01 m for spring and autumn respectively). The range of frequency that is important for the contribution of energy to the seaway also showed seasonal variation. In spring the energy content is ranged between 0.4 to 1.8 rad/sec. In summer the range of frequency which contributes in the energy content is much lower (between 0.6 to 1.4 rad/sec). Autumn spectrum has its energy between a range of 0.2 to 1.8 rad/sec and winter spectrum between 0.4 to 2 rad/sec. The frequency at which maximum energy is supplied varied as well. Spring, summer and autumn all had their maximum energy supplied at 1 rad/sec but in winter the maximum energy was supplied at 1.4 rad/sec. Swell condition was different for different seasons. Winter showed swell condition ranged over comparatively more low-frequency bands. Swell effect is more prominent in lower sea states than the higher sea states.

The reason behind the variations of the wave spectra is the varying atmospheric and climatic conditions observed during the different seasons. The atmospheric circulation, and consequently the surface winds are impelled by these climatic variations[39, 40]. As surface wind waves (and storm surges) and its spectrum are generated and shaped by the action of wind on the sea surface[32], so properties of wind-waves will vary in response to the climatological variations in the surface atmospheric circulation. Therefore, variations will occur in the spectrum of the waves as well. Variation in swell in different seasons[41] is another cause that triggers variations in the wave spectral characteristics. Monsoon intensity changes with season[42]. This tends to bring inter seasonal changes in the wave spectral characteristics[11]. Summer season shows the highest values of energy density. This is probably due to higher monsoon intensity in summer season. Fetch length variation probably caused the spectral variations as well[32]. Longer fetch in summer presumably resulted in its rough sea state. Other spectra vary accordingly.

Measured spectra of the four seasons showed variation from ITTC spectrum, JONSWAP spectrum, Scott spectrum and Ochi-Hubble bi-modal spectrum of respective seasons. As mentioned earlier, the spring, the summer and the autumn spectra can be best compared to the Scott spectra of their respective seasons. Al-though the energy content is different, they show somewhat comparable shape. Winter spectrum, on the other hand, does not show similarity with any of these. It gives a unique representation. There might be some probable reasons for these deviations. The ITTC formulation has some limitations: fetch limitations, state of development or decay, sea-floor topography, local currents and swell limitations[43]. Hasselmann et al.[36] found that the JONSWAP spectrum is a fetch-limited wave spectrum. The wave spectrum is never fully developed. It continues to develop through non-linear, wave-wave interactions even for very long times and distances. Therefore in the JONSWAP spectrum, waves continues to grow with distance (or time) and the peak in the spectrum is more pronounced. It has some basic assumptions: North Sea data, limited fetch, uni-directional seas and no swell[43]. These assumptions probably led to the deviation from the measured wave spectra of the northern region of the Bay of Bengal for all seasons. Scott spectral formula is independent of the wind speed, fetch or duration and represents a fully developed sea[35, 37] and Ochi-Hubble spectrum incorporates the effect of swell[35, 38]. Real-time wave data of the northern region of the Bay of Bengal is used in this study. Thus new wave spectra for the four seasons are obtained, different from other known spectral formulations.

CONCLUSION

The principal focus of the study is to develop the wave spectrum of the northern region of the Bay of Bengal. How the wave spectrum varies with the change of seasons was analyzed as well. The mean wave period and significant wave height, varying with seasonal changes, were investigated. The correction factors of the wave spectra in the four seasons showing the deviation from Rayleigh distribution were calculated. The equations of the wave spectra using the parameters mean wave period and significant wave height were derived. The seasonal analysis shows that the energy content in summer is the highest and that in winter is the lowest. The comparison with other spectra for each season indicates that the result is encouraging. Thus, using the derived formulae, the wave spectrum of the northern part of Bay of Bengal in every season can be obtained, thereby, opening the door to new research opportunities in this region.

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REFERENCES

1. Hanson, J.L., and Phillips, O.M., 1999, "Wind sea growth and dissipation in the open ocean", Journal of physical oceanography, 29(8), pp. 1633–1648.https://doi.org/10.1175/1520-0485(1999)029<1633:WSGADI>2.0.CO;2.

2. Ochi, M.K., 2005, *Ocean waves: the stochastic*

approach, Vol. 6, Cambridge University Press.
3. Stewart, R.H., 2008, *Introduction to physical oceanography*, Texas A & M University Texas.
4. Earle, M., 1984, "Development of algorithms for separation of sea and swell", National Data Buoy Center Tech Rep MEC-87-1, Hancock County, 53, pp. 1–53.
5. Panchang, V.G., Xu, B., and Demirbilek, Z., 1999,"Wave Prediction Models for Coastal Engineering Application", Developments in Offshore Engineering,pp.163–194.https://doi.org/10.1016/b978-088415380-1/50023-6.
6. Chakrabarti, S., 2005, *Handbook of Offshore Engineering* (2-volume set), Elsevier.
7. National Research Council, 2010, *Advancing the science of climate change*, Washington D.C., National Academies Press. https://doi.org/10.17226/12782.
8. Weisse, R., 2010, *Marine climate and climate change: storms, wind waves and storm surges*, Springer Science & Business Media.
9. Trenberth, K.E., and Hurrell, J.W., 1994,"Decadal atmosphere-ocean variations in the Pacific", Climate Dynamics, 9(6), 303–319. https://doi.org/10.1007/s003820050027.
10. Janssen, P., Doyle, J.D., Bidlot, J., Hansen, B., Isaksen, L., and Viterbo, P., 2002, "Impact and feedback of ocean waves on the atmosphere", Advances in Fluid Mechanics, 33, pp. 155–198.
11. Kumar, V.S., and Nair, M.A., 2015, "Inter-annual variations in wave spectral characteristics at a location off the central west coast of India", Annales Geophysicae 33(2), pp. 159–167. https://doi.org/10.5194/angeo-33-159-2015.
12. Sanjiv, P.C., SanilKumar, V., Johnson, G., Dora, G.U., and Vinayaraj, P., 2012, "Interannual and seasonal variations in nearshore wave characteristics off Honnavar, west coast of India.
13. Zaitseva-Pärnaste, I., Suursaar,Ü.,Kullas, T., Lapimaa, S., and Soomere, T., 2009,"Seasonal and long-term variations of wave conditions in the northern Baltic Sea", Journal of Coastal Research, pp. 277–281.
14. Allan, J.C., and Komar, P.D., 2000, "Spatial and temporal variations in the wave climate of the North Pacific", *Report to the Oregon Department of Land Conservation and Development*,pp. 46
15. Kamranzad, B., Etemad-shahidi, A., and Chegini, V., 2013,"Assessment of wave energy variation in the Persian Gulf", Ocean Engineering, 70, pp. 72–80. https://doi.org/10.1016/j.oceaneng.2013.05.027.
16. Lee, B.C., Wu, L.C., Doong, D.J., and Kao, C.C., 2007, "Seasonal variations of wind and waves over Taiwan waters", Marine Geophysical Researches, 28(3),pp.183–190.https://doi.org/10.1007/s11001-007-9025-6.
17. Patra, A., and Bhaskaran, P.K., 2016,"Trends in wind-wave climate over the head Bay of Bengal region", International Journal of Climatology, 36(13), pp. 4222–4240. https://doi.org/10.1002/joc.4627.
18. Ching-Piao, T., Ching-Her, H., Chien, H., and Hao-Yuan, C., 2012, "Study on the wave climate variation to the renewable wave energy assessment", Renewable Energy, 38(1), 50–61. https://doi.org/10.1016/j.renene.2011.06.041.
19. Corbella, S., and Stretch, D.D., 2014, "Directional wave spectra on the east coast of South Africa", Journal of the South African Institution of Civil Engineering= Joernaal van die Suid-Afrikaanse Instituut van SivieleIngenieurswese, 56(3), pp. 53–64.
20. Espejo, A., Camus, P., Losada, I.J., and Méndez, F.J., 2014, "Spectral ocean wave climate variability based on atmospheric circulation patterns", Journal of Physical Oceanography, 44(8), pp. 2139–2152. https://doi.org/10.1175/jpo-d-13-0276.1.
21. Bromirski, P.D., Cayan, D.R., and Flick, R.E., 2005, "Wave spectral energy variability in the northeast Pacific", Journal of Geo-physical Research: Oceans,110(C3).https://doi.org/10.1029/2004jc002398.
22. Shanas, P.R., and Kumar, V.S., 2014, "Trends in surface wind speed and significant wave height as revealed by ERA-interim wind wave hindcast in the Central Bay of Bengal", International Journal of Climatology, 35(9), pp. 2654–2663. https://doi.org/10.1002/joc.4164.
23. Jena, B.K., Patra, S.K., Joseph, K.J., and Sivakholundu, K.M., 2017,"Seasonal Variation in Nearshore Wave Characteristics off Cuddalore, Southeast Coast of Tamil Nadu, India", Current Science, 112(10), pp. 2115.
24. Potemra, J.T., Luther, M.E., and O'Brien, J.J., 1991, "The seasonal circulation of the upper ocean in the Bay of Bengal", Journal of Geophysical Research: Oceans, 96(C7), pp. 12667–12683.
25. Cheng, X., Xie, S.P., McCreary, J.P., Qi, Y., and Du, Y., 2013,"Intraseasonal variability of sea surface height in the Bay of Bengal", Journal of Geophysical Research: Oceans, 118(2), pp. 816-830.
26. Glejin, J., Kumar, V.S., and Nair, T.B., 2013, "Monsoon and cyclone induced wave climate over the near shore waters off Puduchery, south western Bay of Bengal", Ocean Engineering, 72, pp. 277–286. https://doi.org/10.1016/j.oceaneng.2013.07.013.
27. Chaudhary, A., Basu, S., Kumar, R., Prasad, K., and Sharma, R., 2015, "Retrieving significant wave height in the Indian Ocean near Visakhapatnam using Jason-2 altimeter data", Remote Sensing Letters, 6(4), pp. 286–294.https://doi.org/10.1080/2150704x.2015.1029091.
28. Kumar, V.S., Dubhashi, K.K., and Nair, T.M.B., 2014, "Spectral wave characteristics off Gangavaram, Bay of Bengal", Journal of Oceanography, 70(3), pp. 307–321. https://doi.org/10.1007/s10872-014-0223-y.
29. Islam, M.T., Uddin, M.G., Chakma, T.B., and Chowdhury, M.Z.R., 2014,"Feasibility Study of Ocean Wave of the Bay of Bengal to Generate Electricity as a Renewable Energy with a Proposed Design of Energy

Conversion System", International Journal of Renewable Energy Research (IJRER), 4(2), pp. 445–452.
30. Trenberth, K.E., 1983, "What are the seasons?", Bulletin of the American Meteorological Society, 64(11), pp. 1276–1282.
31. Flather, R.A., 1994,"A storm surge prediction model for the northern Bay of Bengal with application to the cyclone disaster in April 1991", Journal of Physical Oceanography, 24(1), pp. 172–190. https://doi.org/10.1175/1520-0485(1994)024<0172:asspmf>2.0.co;2.
32. Bhattacharyya, R. 1978, *Dynamics of marine vehicles*, John Wiley & Sons Inc.
33. Prat, M.C., 2008, *Overview of ocean wave statistics*, Doctoral dissertation, Universitat Politècnica de Catalunya, Escola Tècnica Superior d'Enginyers de Camins, Canals i Ports de Barcelona, Departament d'Enginyeria Hidràulica, Marítimai Ambiental, (Enginyeriade Camins, Canals i Ports).
34. Stansberg, C., Contento, G., Hong, S.W., Irani, M., Ishida, S., and Mercier, R., 2002, "The specialist committee on waves final report and recommendations to the 23rd ITTC", *Proceedings of the 23rd ITTC*, vol. 2, pp. 505-551.
35. Sundar, V., 2015, "Description and analysis of random waves", *Ocean Wave Mechanics*, John Wiley & Sons Ltd., pp. 117–153. https://doi.org/10.1002/9781119241652.ch6.
36. Hasselmann, K., Barnett, T., Bouws, E., Carlson, H., Cartwright, D., Enke, K., Ewing, J., Gienapp, H., Hasselmann, D., Kruseman, P., et al, 1973,"Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)", Technical Report, Deutsches Hydrographisches Institut.
37. Scott, J., 1965, "A sea spectrum for model test and long-term ship prediction", Journal of ship research, 9(3), pp. 145–152.
38. Ochi, M.K., and Hubble, E.N., 1977, "Six-parameter wave spectra", *Coastal Engineering 1976*, pp. 301-328.
39. Lamb, H.H., 1975, "Our understanding of the global wind circulation and climatic variations", Bird Study, 22(3), pp. 121–141. https://doi.org/10.1080/00063657509476457.
40. Letcher, T.M., 2015, *Climate change: observed impacts on planet Earth*, Elsevier.
41. Ethamony, P.V., Rashmi, R., Samiksha, S., and Aboobacker, V.M., 2013, "Recent studies on wind seas and swells in the Indian Ocean: a review", The International Journal of Ocean and Climate Systems, 4(1),pp.63–73.https://doi.org/10.1260/1759-3131.4.1.63.
42. Loo, Y.Y., Billa, L., and Singh, A. 2015,"Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia", Geoscience Frontiers 6(6), pp. 817–823. https://doi.org/10.1016/j.gsf.2014.02.009.
43. Techet, A., 2005, *13.42 design principles for ocean vehicles*.

APPENDIX

The data used in the study is obtained from the website of INCOIS. Data of 5 days of the month of March only is reproduced here in Table A1 for perusal.

Table A1: Wave data of 5 days of March'15

Dates	Time	Wave Height(m)	Wave Period(s)
1-Mar-15	12:00 AM	0.6445	7.3242
	3:00 AM	0.7031	8.3008
	6:00 AM	0.5273	6.7383
	9:00 AM	0.6445	8.3008
	12:00 PM	0.5859	7.5195
	3:00 PM	0.4688	5.6641
	6:00 PM	0.5273	5.6641
	9:00 PM	0.5273	5.6641
2-Mar-15	12:00 AM	0.4688	5.8594
	3:00 AM	0.4688	6.4453
	6:00 AM	0.5273	6.6406
	9:00 AM	0.5273	7.5195
	12:00 PM	0.5273	4.1992
	3:00 PM	0.5859	4.5898
	6:00 PM	0.5859	5.0781
	9:00 PM	0.5859	4.8828
3-Mar-15	12:00 AM	0.5273	4.8828
	3:00 AM	0.5859	5.1758
	6:00 AM	0.5273	5.4688
	9:00 AM	0.5859	5.4688
	12:00 PM	0.5859	5.1758
	3:00 PM	0.7031	6.0547
	6:00 PM	0.6445	6.8359
	9:00 PM	0.7031	8.2031
4-Mar-15	12:00 AM	0.7031	7.7148
	3:00 AM	0.7031	7.4219
	6:00 AM	0.8203	8.0078

	9:00 AM	0.7617	6.8359
	12:00 PM	0.8203	7.3242
	3:00 PM	0.7617	6.543
	6:00 PM	0.7617	6.6406
	9:00 PM	0.8789	6.1523
5-Mar-15	12:00 AM	1.0547	6.543
	3:00 AM	0.8203	5.3711
	6:00 AM	0.8789	6.9336
	9:00 AM	0.8789	6.4453
	12:00 PM	0.8203	5.5664
	3:00 PM	0.9961	5.4688
	6:00 PM	0.9961	5.4688
	9:00 PM	1.2891	6.25