Climate Change Impacts on Seasonal Wave Climate of the Western Coast of Sri Lanka

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Abstract: *Climate change and climate change driven impacts are most widely argued topics among contemporary researchers and scientists. Broadly there are two schools of philosophies that process entirely contrasting concepts about this whole concept of climate change and its impacts. While one of the concepts state about frequently varied climate change and occurrence of extreme weather events the others are banking upon the concept that there is no climate change and it is only the indifferences in occurrence of weather and climate events. The title of this study itself implies the fact that this research study supports the concept of climate change and its probable impacts, thus leaving out the other approach on climate change. Extensive concentrations of green house gasses emitted to the earth's atmosphere and vast amounts of aerosols govern the majority of anthropogenic causes for climate change, while many of the natural causes such as changes in solar radiation also contribute immensely to earth's climate change. Absence of detailed studies carried out on investigating probable impacts on wave climates due to projected climate changes is one of the major drawbacks in handling the unique coastal eco systems in Sri Lanka. As a country where coastal resources play a major role in its development, it is absolutely necessary to have a clear idea about the probable impacts that could arise on its coastal areas. This detailed investigation provides vital information on probable impacts that might cause on the western coast of Sri Lanka under the influence of global climate change.The outcomes of this study indicate that there is certain threat to the coasts in Sri Lanka due to a considerable increment in mean wave height and shifted wave directions. It also indicates that not only the number of extreme wave events increase very significantly but also its intensity upsurges in a considerable amount as well, while indicating a major shift in seasonal wave climate that prevails along the western coast of Sri Lanka. This probable shift of seasonal wave climate of the western coast should be considered seriously, since many of its socio-economic activities are directly related to this seasonal wave climate variation.*

Keywords: *Climate Change impacts, seasonal wave climate shift, mean wave height and direction*

1. INTRODUCTION

Changes in the Earth's climate and its possible impacts belong to most widely discussed scientific problems in the present era. These climate changes occur due to both internal variability within the climate system and external factors, which can be either anthropogenic or natural. Increasing concentration of atmospheric greenhouse-gases tends to warm the Earth's surface and its lower atmosphere, while an increase in some types of aerosols tends to cool it (Houghton et al., 2001). Natural factors, such as changes in solar output or explosive volcanic activity, can also cause radioactive forcing and hence influence the Earth's climate. Complex climate models are required to provide detailed estimates of feedbacks and regional features in the climate system. Although confidence in the ability of these models to provide useful projections of future climate has improved on a range of space and time-scales, the present-day climate models cannot yet simulate all aspects of climate (Houghton et al., 2001). For example, there are particular uncertainties associated with clouds and their interaction with radiation and aerosols. Besides, climate model simulations are a combination of a forced climate change component together with internally generated natural variability. The internal variability of the global and regional climate system adds a further level of uncertainty in the evaluation of a climate change simulation.

As an important element of the climate system, ocean wave heights (among many other ocean surface characteristics) could be affected by anthropogenic forcing. However, ocean wave heights are not directly available from the output of global climate models. Useful projections of future wave height climate need to be produced through dynamical or statistical ‘‘downscaling’’ approaches, just like other regional climate change information. Therefore, there are various sources of uncertainty in the generation of ocean wave height climate change projections (Hamer et al., 2010a).

Within the context of climate change, one of the recurrent questions is how this change could impact waves and thus wave-dominated coasts. As an example, the Western Coast of Sri Lanka is bounded by the Indian Ocean and it is characterized by intense human activities, such as sea transport, fishing, coastal shipping, ports, seaside resorts, touristic sandy beaches and surfing areas. Since the said coast is completely open to the ocean, its wave climate is characterized by swells and storms generated by strong winds in the Indian Ocean. In the work done by Wang & Swail, 2006, it was mentioned that the changes in wave conditions could even modify the coastal morphology and hence impact the human activities as well. In the context of global warming, significant climate changes at the oceanic basin scale could modify the wave climate. General Circulation Models (GCM) indeed project atmospheric changes such as a poleward shift of storm tracks (Yin, 2005) or a decrease of the total number and intensity of cyclones in the Northern Hemisphere (CATTO et al., 2011). Occurrence of such kind of changes in wind can make a significant impact on the resulting wave climate, in terms of wave height, period and direction.

Concerning the future wave climate, work done by Christensen et al., 2007 have highlighted the fact that there is a vast lack of information on potential changes in regional wave climate. However, a significant work is yet to be carried out with respect to the possible climate change driven wave climate changes in the Indian Ocean, which will indicate the possible impacts to the western coast of Sri Lanka. The aim of the study carried out was to provide more rigorous projections of the offshore ocean wave climate of the western coastline of Sri Lanka, to provide a suitable dataset, which can be used to assess the possible coastal impacts of climate change in the region, under the forcing of future climate scenarios.

2. OBJECTIVES AND METHODOLOGY OF THE RESEARCH STUDY

2.1. Objectives of the Research Study.

(i) Set up and calibrate a wave model that is capable of predicting the off-shore (deep water) wave climate around Sri Lanka, given the wind field over the relevant portion of the Indian Ocean.
(ii) Application of the said wave model for different scenarios of climate change and environment.

2.2. Research Methodology.

(i) Selection of an appropriate wave generation model.
   a. Possible models are MIKE SW, SWAN, WAM and WW3, and out of these WW3 and SWAN models were used as the model.
(ii) Acquisition of necessary wind data sets for wave modelling process.
   a. Possible sources for actual (historical) wind data are re-analysed wind data from global models (ECMWF, NOAA), Satellite measurements (Quickscat, Adeos) and Wind data from NOAA was used in the study as the historical wind data set.
   b. Predicted wind data (CCAM wind data) was provided by the CSIRO, Australia. The same wind model was used to generate the wind data for the Thailand study as well.
(iii) Acquisition of necessary deep-water wave data for the research domain to calibration and validation of the wave model.

   a. The possible sources are Satellite altimetry (TOPEX/POSEIDON, JASON), SAR measurements by satellites (ERS), Wave hind casts from global models (ECMWF, NOAA) and limited deep-water wave measurements obtained off Sri Lanka.

(iv) Analyses of predicted wind data sets and determine the bias correction procedure if that is necessary.

(v) Set up the wave model to cover an appropriate domain around Sri Lanka, relevant to the data availability and the needs of the study. (As shown in Figure 1)

   a. For this study 300 x 300 area will be taken as the domain (Latitude -8^0 to 22^0 and Longitude 65^0 to 95^0)

(vi) Run the model with the predicted future wind field to predict the future wave climate scenarios.

(vii) Analyzing the differences in the wave climates for the current and future scenarios and assessing their impacts on various uses of the coastal seas.

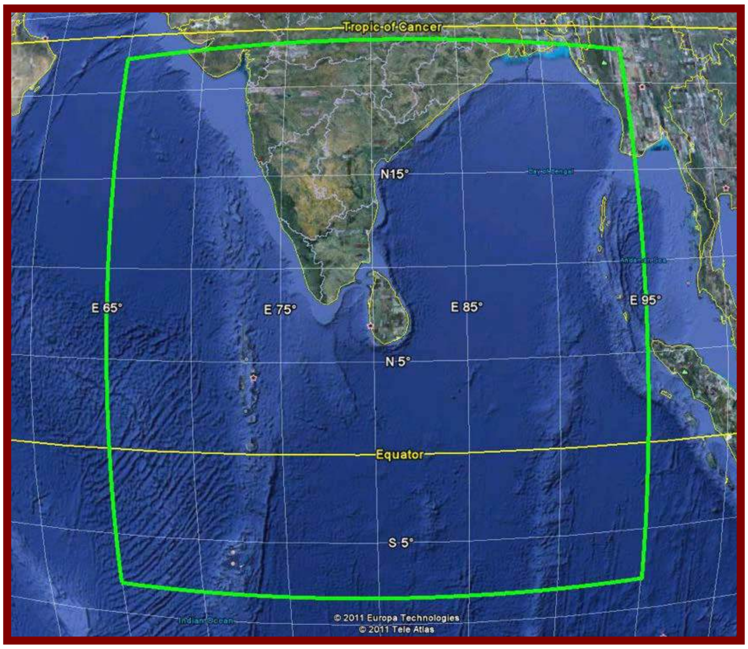

Figure 1. Domain Area of the Study

3. APPROACH TO THE RESEARCH PROBLEM

One of the most critical issues in wave modeling with future climate change projections is the uncertainty related to the projection of Regional Climate Changes. McInnes *et al.*, 2007 has pointed out the fact that there are three main sources of uncertainty to be considered when producing projections of global warming-induced climate change for a region for a given year in the future.

(i) The uncertainty in the future evolution of greenhouse gas concentrations in the atmosphere.

(ii) The uncertainty in how much the global average surface temperature will respond to increases in atmospheric greenhouse gas concentrations.

(iii) The uncertainty in how changes to the climate as a result of global warming will vary spatially and hence how the climate of the region under consideration will respond to an increase in global average surface temperature.

The first uncertainty can be addressed by considering different plausible storylines of future global demographic, economic and technological change. The Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios has provided greenhouse gas emission scenarios associated with a suite of such storylines. The second uncertainty can be addressed by considering the future rates of future global warming in simulations of different climate models forced with increases in atmospheric greenhouse gas concentrations arising from emission scenario corresponding to the Special Report on Emission Scenarios (SRES). The third uncertainty, the uncertainty in the response of the regional climate to a given global warming value, can be addressed by considering the response of the climate of the region of interest to global warming in multiple climate models.

Although the work done relating to wave climate with future climate changes are rare to find for the Sri Lankan context, there are number of successful benchmark attempts that have been made in various parts of the world to address the said issue. Almost in all such research work carried out, the outcomes claim a significant relationship between the future wave climate and its forcing conditions that are to be caused by future climate change scenarios.

The work done by Hamer et al., 2010a emphasize the fact that insufficient projections of wave climate were available to assess the effects of probable climate change impacts on erosion of the world's coasts. According to the said work, at present, a considerable research effort is placed into regional ocean wave projections, with forcing conditions derived from a few selected emission scenarios from a few selected GCMs. It has identified several shortcomings of such an approach, as the following.

(i) Limitations of statistical confidence in the projections.
(ii) Additional effort requirements in modelling due to repeated model runs.
(iii) Laps in the global coverage, including the crucial areas that are most likely to be at risk due to changing wave conditions.

The propose solution given in the said study for this problematic scenario was to shift to global projections. The aim should be to use different wave models and statistical downscaling approaches to produce ensembles of wave projections that correspond to climate projections from different climate models for different emission scenarios. When combined, a distribution of projections will be available that will allow an assessment of all three levels of uncertainty (associated with forcing, climate models, and downscaling methods, respectively), presenting projections within statistical confidence intervals. The proposed design will provide suitable data on a global scale for carrying out surface ocean wave projections, focusing on mid- and late-twenty-first-century time slices, to service the increasing demands of the coastal impacts community. Future studies could include dynamic coupling of wave processes into coupled ocean–atmosphere global climate models (Hamer et al., 2010a).

According to work done by Swail & Wang, 2005, results of ocean wave climate change scenarios for the northern hemisphere oceans for the twenty-first century show that significant changes can be anticipated in both the North Atlantic and the North Pacific under all the three forcing-scenarios. The rate and sign of the projected future wave height changes are not constant throughout the 21st century and in some regions, these appear to be very much dependent on the forcing conditions as well. The rate of change appears to have a positive relationship with the rate of increase in the greenhouse-gases forcing.

4. USE OF WAVEWATCH III AND SWAN MODELS TO MODEL FUTURE WAVE CLIMATES

The basic scientific philosophy of SWAN is identical to that of WAM (Cycle 3 and 4) and it uses the same formulations for the source terms. On the other hand, SWAN contains some additional formulations, primarily for shallow water. Moreover, the numerical techniques are very different. WAVEWATCH III not only uses different numerical techniques but also different formulations for the wind input and white capping (The Wave Model Development and Implementation Group, 1988).

When SWAN is nested with WAVEWATCH III, it was noted that the boundary conditions for SWAN provided by WAVEWATCH III are not consistent, even the same physics are being used. The potential reasons are manifold such as the differences in numerical techniques employed and implementation for geographic area (spatial and spectral resolutions, coefficients, etc.) (Chawla & Tolman, 2007), (Tolman, 2010), and (Cavaleri et al., 2007).

To overcome this issue, the deep-water boundary of SWAN nest was located in WAVEWATCH III, where shallow water effects do not dominate. This is primarily important to avoid the existence of large discontinuities between the two models. At the same time, the spatial and spectral resolutions were adjusted so that it will not differ largely from one another, in order to avoid additional modifications of the model layout (Cavaleri et al., 2007), and (Chawla & Tolman, 2007).

Since SWAN in coded in such a manner, so that the scientific findings with another wave model could be shared with SWAN. Similarly, SWAN could be readily nested in WAVEWATCH III for collaborative modelling of wave climates from Deep Ocean to shoreline. In this research study, the said similarities have been extensively exploited, in order to couple the WW3 and SWAN together to model the necessary outputs. (Cavaleri et al., 2007), (Chawla & Tolman, 2007), (The SWAN Team, 2010), (The SWAN Team, 2011 (c)), and (The Wave Model Development and Implementation Group, 1988).

5. MODELLED WAVE OUTPUTS

The outputs obtained via wave modelling are for three different time spans, could be identified as the following.

(i) Past wave climate - year 1981 to 2000
(ii) First future wave climate – year 2041 to 2060
(iii) Second future wave climate - year 2081 to 2100)

In order to match with the overall project requirements, outputs were obtained for a point near Colombo. This was also governed by the fact of available wave measurements. Most of the available wave measurements are for Colombo, thus it is convenient to compare the modelled wave output against the available wave measurement.

The comparison of the variation in wave climates were carried out with respect to the modelled past wave climate and the comparisons made reviled the fact that there might be a considerable differences in future wave climates along the western coast of Sri Lanka. Comparison of mean wave climates indicates an increment of about 6.5% for projected mean wave height during year 2041 – 2060 and 8.5% increment for the same during year 2081 – 2100. The mean wave direction of the first future wave climate shows an increment of about 8% and that is slightly reduced during the second projected wave climate. Although these are not very alarming in magnitudes, it indicates a significant variation, when considered with respect to the usual seasonal wave climates prevailing in Sri Lanka.

The predicted wave climate changes could be considered in correspond to main rainy seasons prevailing in Sri Lanka. Sri Lanka has two major monsoon periods and two inter-monsoon periods, where the time periods are to be considered as the following.

- Southwest monsoon – May to September
- Northeast monsoon – December to February
- First inter-monsoon – October to November
- Second inter-monsoon – March to April

Investigating the predicted changes during these major seasons is particularly important, due to the fact that the wave condition along the western coast of Sri Lanka is expected to exhibits major seasonal variations, especially during the southwest monsoon period. Table 1 indicates the predicted wave climates during the two major monsoon periods.

Table 1 Comparison of predicted wave climates during the monsoon periods

		Southwest Monsoon			**Northeast Monsoon**		
		1981	**2041**	**2081**	**1981**	**2041**	**2081**
Wave Heights	Mean	1.06	1.12	1.11	1.06	1.14	1.18
	Var	0.2047	0.2558	0.2808	0.2401	0.2317	0.2372
	Std	0.45	0.51	0.53	0.49	0.48	0.49
Wave Directions	Mean	249.88	269.84	267.32	247.47	270.12	272.27
	Var	279.51	294.81	371.58	291.79	335.40	383.66
	Std	16.72	17.17	19.28	17.08	19.31	19.59

Similarly, it is necessary to have a comparison of the predicted wave climates for the two inter-monsoon periods as well. Table 2 consists of the necessary information for the said comparison of predicted wave climates.

Table 2 Comparison of predicted wave climates during the inter-monsoon periods

		First Inter-Monsoon			Second Inter-Monsoon		
		1981	**2041**	**2081**	**1981**	**2041**	**2081**
Wave Heights	Mean	1.06	1.09	1.13	1.02	1.14	1.16
	Var	0.1975	0.1757	0.2648	0.2755	0.3081	0.2620
	Std	0.44	0.42	0.51	0.52	0.56	0.51
Wave Directions	Mean	249.30	264.48	272.14	254.44	277.92	267.17
	Var	282.35	429.79	291.65	384.07	362.05	265.55
	Std	16.80	20.73	17.08	19.60	19.03	16.30

The above two tables indicate the variation of predicted wave climates during the two main monsoon periods and the two inter-monsoon periods prevailing in Sri Lanka. According to the modelled results, it can be observed that wave heights are higher during the Northeast monsoon period than those during the Southwest monsoon, which is not compatible with the expected monsoonal variations. However, it could be also noted that the inter-monsoonal wave heights are also at higher magnitudes. Since these observations are at variance with the existing pattern of wave heights, it could be concluded that the starting time period of the two main monsoons, as well as the two inter-monsoon periods have shifted slightly (i.e starting time period is being delayed slightly).

However, it is also possible that the inter-monsoon periods providing higher magnitudes of wave heights and the effects of the inter-monsoons extending over a longer period than that at present, thus the effects of the two main monsoon periods are being over shadowed by the two inter-monsoon periods. The following plots also support the said arguments and provide a better understanding about the variations in wave climates during the monsoonal periods.

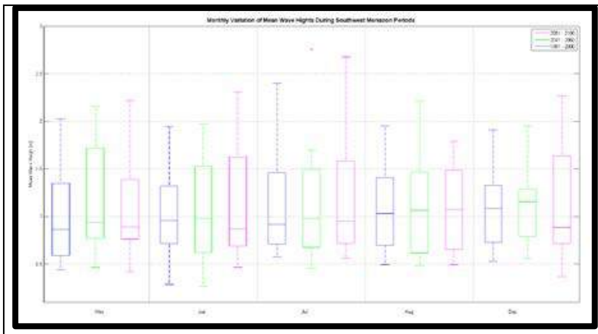

Figure 2. Comparison of predicted wave heights during Southwest monsoon

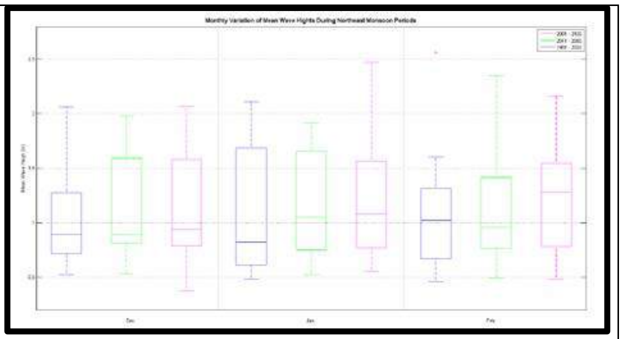

Figure 3. Comparison of predicted wave heights during Northeast monsoon period

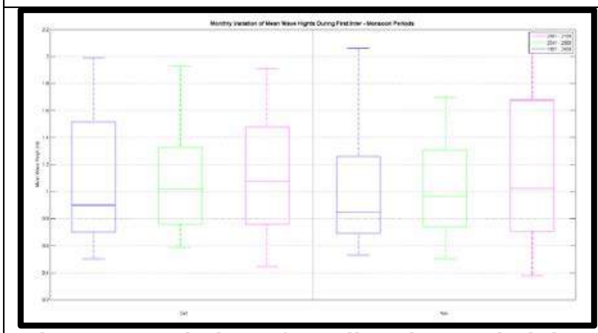

Figure 4. Variation of predicted wave heights during the first inter-monsoon period

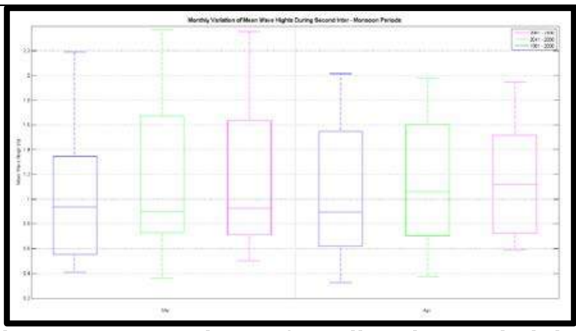

Figure 5. Comparison of predicted wave heights during the second inter-monsoon period

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

Beside that fact that percentage values are not so significantly high for predicted mean wave climates, corresponding increment in mean wave height for the first projected wave climate is 7 cm and that value increases by another 2 cm for the second projected wave climate, resulting in a total of 9 cm increment for the mean wave height by the end of 21^{st} century. This is a considerable amount of increment, given the fact that it may cause increased erosion and disruption along the heavily populated western coast of Sri Lanka.

The probable variations in the seasonal wave climate are also with considerable significance, because western coastal belt of Sri Lanka is heavily dependent upon the seasonal variations of the wave climate. Almost all the economic activities, such as fishery and tourism are functioning according to the prevailing wave conditions. If a shift in usual wave climate is to be observed, it can cause negative influences on the existing socio-economic system of the area. On the other hand, if the duration and the severity of extreme wave climate is to be extended over longer periods, it also causes major setbacks to the usual day to day life of the people, who are solely dependent upon fishery and tourism industry.

On the other hand, modelled wind data proved to be a very good input to force the wave models, as it was available at a higher resolution (0.5 degree) for the domain area of study. Therefore, it is also concluded that although there are certain issues that exist with the consistency of modelled wind data, together with necessary modifications to wave model, it could be used to force wave models to obtain very useful information.

The domain area for the study was restricted by the project requirements. However, if a more detailed study to be carried out for the Indian Ocean region, wind data should be available for a larger domain, covering a lager area of the Indian Ocean. This research study was not carried out at such a high detailed level of the entire Indian Ocean, thus the availability of modelled wind data was sufficient for this particular research study.

7. REFERENCES

CATTO, J.L., SHAFFREY, L.C. & HODGES, K.I., 2011. Northern Hemisphere Extratropical Cyclones in a Warming Climate in the HiGEM High-Resolution Climate Model. American Meteorological Society.

Cavaleri, L., Alves, J.H.G.M. & Ardhuin, F., 2007. Wave Modelling - The State of the Art. Progress in Oceanography, 75, pp.603 - 674.

Charles, E. et al., March 2012. Climate change impact on waves in the Bay of Biscay, France.

Chawla, A. & Tolman, H.L., 2007. Automated grid generation for WAVEWATCH III. Technical Note. U. S. Department of Commerce.

Christensen, J.H. et al., 2007. Regional Climate Projections. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church, J.A. & White, N.J., 2006. A 20th Century Acceleration in Global Sea-Level Rise. GEOPHYSICAL RESEARCH LETTERS, Volume 33.

Church, J.A., Woodworth, P.L. & Aarup, T., 2010. Underestanding Sea-Level Rise and Variability. Wiley-Blackwell Publishing Ltd.

De Bruin, G.H.P., Russell, B.C. & Bogusch, A., 1994. The marine fishery resources of Sri Lanka. Rome, Italy: Food and Agriculture Organization of the UN.

Dodet, G., Bertin, X. & Taborda, R., 2010. Wave Climate Variability in the North - East Atlantic Ocean Over the Last Six Decades. Ocean Modelling, 31, pp.120 - 131.

Goto, K., Takahashi, & Oie, , 2011. Remarkable bathymetric change in the nearshore zone by the 2004 Indian Ocean tsunami: Kirinda Harbor, Sri Lanka. Geomorphology.

Hamer, M.A., Mclnnes, K.L. & Ranasinghe, R., 2009. Future Projections of the East Australian Wave Climate. In 11th International Workshop on wave hindcasting and forecasting and coastal hazards. Halifax, Canada, 2009.

Hamer, M.A., Wang, X.L., Church, J.A. & Swail, V.R., 2010a. Coordinating Global Ocean Wave Climate Projections. American Meteorological Society.

Hemer, M., McInnes, K. & Ranasinghe, R., September, 2010b. Investigation of Climate Driven Variations in Offshore Wave Climate Along the NSW Coast. The Centre for Australian Weather and Climate Research.

Houghton, J.T. et al., 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Joseph, L., n.d. NATIONAL REPORT OF SRI LANKA on the Formulation of a Transboundary Diagnostic Analysis and Strategic Action Plan for the Bay of Bengal Large Marine Ecosystem Programme.

Kalnay, Kalnay, Kalnay & Kalnay, 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc.

McInnes, K., Macadam, I. & O'Grady, J., 2007. Climate Change Projections for the Wooli Wooli Estuary and Batemans Bay. New South Wales Department of Environment and Climate Change.

Scheffer, H.J., Fernando, K.R.M.D. & Fittschen, T., May, 1994. Directional Wave Climate Study; South-West Coast of Sri Lanka. CCD-GTZ Coast Conservation Project.

Swail, V.R. & Wang, X.L., 2005. Projection and Analysis of Extreme Wave Climate. JOURNAL OF CLIMATE, VOLUME 19, pp.5581-605.

The Wave Model Development and Implementation Group, 1988. The WAM Model - A Third Generation Ocean Wave Prediction Model. Journal of Physical Oceanography , 18, pp.1775 - 1810.

Tolman , H.L., 2009. User manual and system documentation of WAVEWATCH III version 3.14. Technical Note. U. S. Department of Commerce.

Tolman, H.L., 2010. WAVEWATCH III Development Best Practices. Technical Note. U. S. Department of Commerce.

Wang, X.L. & Swail, V.R., 2006. Climate Change Signal and Uncertainty in Projections of Ocean Wave Heights. Climate Dynamics, Volume 26, pp.109 - 126.

Yin, J.H., 2005. A Consistent Poleward Shift of the Storm Tracks in Simulations of 21st Century Climate. Geophysical Research Letters.