AN APPROACH TOWARDS WAVE CLIMATE STUDY IN THE PERSIAN GULF AND THE GULF OF OMAN: SIMULATION AND VALIDATION

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Abstract

This article describes the 11-year wave simulation (1992-2002) in the Persian Gulf and the Gulf of Oman using the input data derived from European Center for Medium-Range Weather Forecasts (ECMWF). The ECMWF 10 meter wind field and spectral wave boundary condition at 18°N degree are input into one of the latest versions of numerical wave models (3rd generation) after a few local modifications. Tropical cyclones during the last 30 years in the northern Indian Ocean which affect the Gulf of Oman are regenerated and wave simulation for individual cyclones is carried out. Open boundary of continuous hindcast is also modified in cyclone periods. In-situ and satellite wind and wave data sets are used to evaluate the accuracy of input wind and simulated wave fields. Extreme Value Analysis (EVA) is the next taken stage in which the wave characteristics were calculated for different return periods. Similar analysis is performed on the directional data to find out significance of storms in each direction. Finally, a user-friendly engineering and management tool is developed and verified.

Keywords:Wave Modeling, Tropical Cyclones, Directional Extreme Value Analysis, Persian Gulf, Gulf of Oman, Iranian Wave Atlas

1-Introduction

Wave, the most significant maritime phenomenon, due to its complicated and stochastic behavior is known as one of the most difficult phenomena in engineering studies. The effect of waves on coastal and marine activities urges us to identify the wave characteristics using field measurements, theoretical studies, physical modeling, and numerical simulations. Coastal and harbor engineers generally use these methods to identify wave climate and the highest probable wave characteristics as well as annual attributes of waves. For this reason, countries that take the advantage of contiguity to seas or great lakes have developed a regular plan for studying wave and other marine phenomena.

Thus, a couple of attempts have been undertaken within the last few years on global and regional scales to provide reasonable reconstructions of the past waves condition. Since mid-1980s, several major Numerical Weather Prediction (NWP) centers (ECMWF, U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC), and U.S. National Centers for Environmental Prediction (NCEP)) have operated global spectral ocean wave models in real time and have accumulated the analysis products to form preliminary estimates of the global wave climate. Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Navy Operational Regional Atmospheric Prediction System (NORAPS) at FNMOC, generate a twice-daily suite of atmospheric analyses and forecasts (Bayler and

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Lewit, 1992). After the success of ERA-15 (Sterl et al., 1998), ECMWF performed their second reanalysis, ERA-40 (Caires and Sterl, 2003). In parallel with them, the American National Center for Atmospheric Research and the National Centers for Environmental Prediction (NCEP/NCAR) produced a global reanalysis of the surface wind from 1958-1997 which was used to force the spectral ocean wave model (Cox and Swail, 2001). Although they provide valuable sources for global oceanographic studies, their low resolution for coastal engineering and environmental purposes requires national and regional centers to prepare high-resolution datasets with special attention to the areas of their interests.

In this regard, a forty-year wave hindcast study for the Arabian Sea, emphasizing on the wave climate of Al-Ashkharah in Oman, was performed by Baird & Associates (Dibajnia, 2002). They used a second generation (2G) spectral wave model based on the WAVAD model (Resio, 1981) to simulate wave climate of the Arabian Sea. They also addressed tropical cyclones separately. Ocean weather and DHI Water & Environment jointly did a comprehensive metocean study of the Persian Gulf called PERGOS. It was based on hindcast of a continuous 20-year period (1983-2002) and 108 storms of various dates between 1961 and 2002.

The oceanic region compromised of the Persian Gulf, Strait of hormuz and the Gulf of Oman is one of the most important waterways in the world. In peak periods, one ship passes the Strait of Hormuz every 6 minutes, and approximately 60% of the world marine transport of oil comes from this region (Reynolds, 1993). The Persian Gulf is a marginal sea measuring some 1000 *km* in length and 200-300 *km* in width, covering an area of approximately 226000 km^2. Its average depth is 35 *m* and it attains its maximum depth of 100 *m* near its entrance- the Strait of Hormuz. It is virtually surrounded by arid land and connected to the Gulf of Oman and Indian Ocean only by 60 *km* wide Strait of Hormuz. Qishm Island borders the north side of the strait. The Gulf of Oman is northwestern arm of the Arabian Sea, between the eastern part of the Arabian Peninsula and Iran. It is about 370 *km* wide and 545 *km* long.

Strong winds characterize most desert areas including those bordering the Persian Gulf. The Shamal blows mainly from the North West in the Northern parts of the Persian Gulf, but tends to veer to North as one approaches to the South East. Because wave and surface currents are related to "Shamal" wind, they are directed mainly towards the South East (Purser and Seibold, 1973). In contrast, Gulf of Oman is mainly affected by seasonal winds called monsoons.

The first attempts for studying the wave characteristics for Iranian coastlines began by deploying some wave measurement stations in deep waters of Iranian seas. Together with this basic data, other data sources such as different short period measurements of wave parameters, satellite data, and results of large scale numerical simulations enable us to pursue a hindcast project in Iranian Seas including the Caspian Sea in the North, and the Persian Gulf and the Gulf of Oman in the South titled Iranian Seas Wave Modeling (ISWM).

The main goal of ISWM is to identify the wave climate in Iranian seas using the results of wave simulations. This is performed by employing the latest version of wave numerical models (3rd generation) and the tuning with in-situ measurements and available satellite data. If successfully validated, this data set can be used to compute extreme waves statistics. The ISWM results present the required wave parameters for different applications in harbor and coastal engineering fields. Iranian National Center for Oceanography (INCO), in association with DHI Water & Environment undertook this project.

This paper is organized as follow. First, the methodology and general approach towards the wave hindcast study are briefly described. The in-situ and satellite-measured wind speed and direction and wave height data sets are then introduced. The data has been used for model tuning and result evaluation. EVA results which are of great importance in this research have been completely discussed. Derivative products and conclusions are provided in the remaining parts.

2- Wave hindcast methodology

The purpose of the study is to provide a reasonable reconstruction of the wave conditions and the wave climate over the past 11 years, from 1992 to 2002, for the Iranian coastal area. Hindcast is completed by individual modeling of cyclones coming from north east of Indian Ocean during 1975-2004. The following approach has been adopted for the Persian Gulf and the Gulf of Oman.

2-1- Atmospheric/Ocean forcing

It is accepted that the 3rd generation wave models are satisfactory reliable for many practical applications. Therefore, for reliable wave prediction, it is essential to have reliable input wind fields. The results of any numerical wave hindcast study depend heavily on the quality of the wind data used to drive the model and are, therefore, only as good as the input data (Hubertz et al., 1991). For instance, for a fully developed sea, wave height approximately scale with the square of the wind speed (Tolman, 1998) which implies that an error of about 10% in the driving wind speed will result in an error of at least 20% in the hindcast wave height (Weisse and Feser, 2003). Therefore, obtaining the wind field may be the most problematic task of wind-wave prediction. The following wind sources were evaluated for possible use in generating the long term wave hindcasting.

For long period simulations, however, additional requirements regarding the quality of the wind fields have to be made. For instance, the wind field should be free of any artificial trends. They should be homogeneous in time and for coastal applications, their spatial and temporal resolution should be high enough to resolve the relevant topographic features in the coastline in order to obtain appropriate wave/surge model simulations. While global reanalyses provide a useful product for a variety of studies (e.g., climate studies), their spatial and temporal resolution remains too coarse for many environmental applications, such as ocean or wave modeling in coastal areas (Weisse and Gayer, 2000).

Among the identified wind fields, NCEP/NCAR products have been discarded because of their low spatial resolution for coastal modeling and not covering the required modeling period (1992-2002), regardless of their accuracy. Besides, based on the data assessment, the ERA-40 wind speeds compare better with the in-situ and altimeter observations than the NCEP/NCAR wind speeds (Caires et al., 2002). The other source, U.K. Met Office data set, does not cover the simulation period. The only remaining source is ECMWF 6 hourly 10 m wind field. Both operational and reanalysis data sets were purchased and despite the non-homogeneous output of operational model, it was chosen due to the better agreement with measured data in coastal

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and islands stations and the higher spatial resolution which is an obligation for modeling the narrow strait of Hormuz (Figure 1). The minimum width is only 60 km (0.54 degree) there, which requires high resolution data for input and output parameters. A brief review of global atmospheric models is given in Table 1.

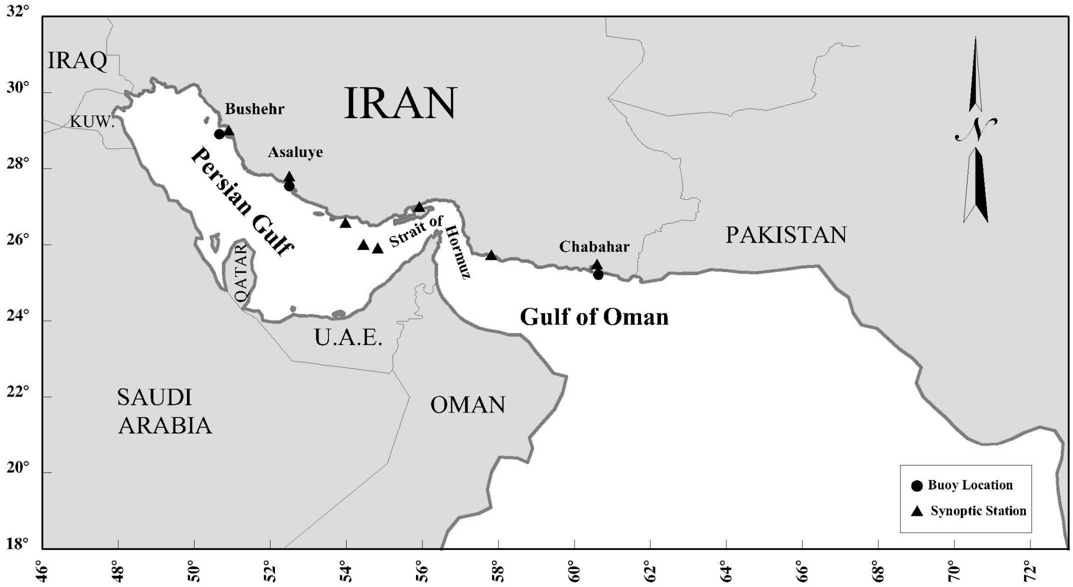

Fig.1- General view of the study area and wind/wave stations

Table 1- Spatial and temporal resolution of global wind fields in the Persian Gulf and the Gulf of Oman

Organization	Production Type	Time Period	Resolution Lat.×Long. (degree)	Time step (Hour)
NCEP/NCAR	Reanalysis	1957-1998	1.25 × 2.5	6
ECMWF	Operational	1 Jan.1985-30 Apr.1985	1.875 × 1.875	6
		1 May 1985-16 Sep. 1991	1.125 × 1.125	
		17 Sep.1991-20 Nov. 2000	0.56× 0.56	
		21 Nov. 2000- 31 Jan. 2006	0.35× 0.35	
		1 Feb. 2006 up to now	0.22 × 0.22	
	Reanalysis	1957-2002	1.125 × 1.125	6
U.K MET OFFICE	Operational	1999 up to now	0.55 × 0.833	6

The wave parameters on the open boundary of the Gulf of Oman can be obtained from ECMWF Global wave model, both spectral and parametric data, and U.K. Met Office parametric wave data. A few short periods were simulated using these boundary data and the results comparisons with wave measurements showed that a better agreement can be achieved using ECMWF spectral wave data.

Due to the importance of EVA for marine and coastal studies, cyclones, which might have the return period longer than 11-year simulation period, have been considered separately. Thus, cyclones specifications including their time, maximum wind speed, and trace within latest 30 years (1975-2004) were obtained from Unisys Weather.

2-2- Wave modeling

The wave model used for this study is Mike 21 Spectral Wave model, a 3rd generation spectral wind-wave model based on unstructured meshes (Figure 2). DHI Water & Environment (2003) has developed this model that simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal area. It has been extensively tested and verified at a range of sites throughout the world. The wave spectrum is resolved in 16 directional bins (22.5° angular bandwidth) and 25 frequency bins (Df/f=0.1).

Hourly output is adopted on a regular grid spacing of 0.125° in latitude and longitude and the modeling results in smaller bays and estuaries are also available via unstructured output files. Test runs and model tuning was done separately for two basins (Persian Gulf and Gulf of Oman). White Capping parameters, wave breaking parameters and bottom friction coefficient are selected by changing them in their normal range to obtain best agreement for both wave height and period. Wind fields are interpolated at 3 hours intervals, while the model execution time step is 300 seconds. Time step is automatically getting smaller by the model in the fine mesh near the Iranian coasts. Output wind and wave parametric data up to 64° E and 22° N are archived for users at 6 hourly intervals at all model grid points, while directional spectra are archived at 6 hourly intervals every 0.125° in Iranian coasts and every 0.25° in other areas.

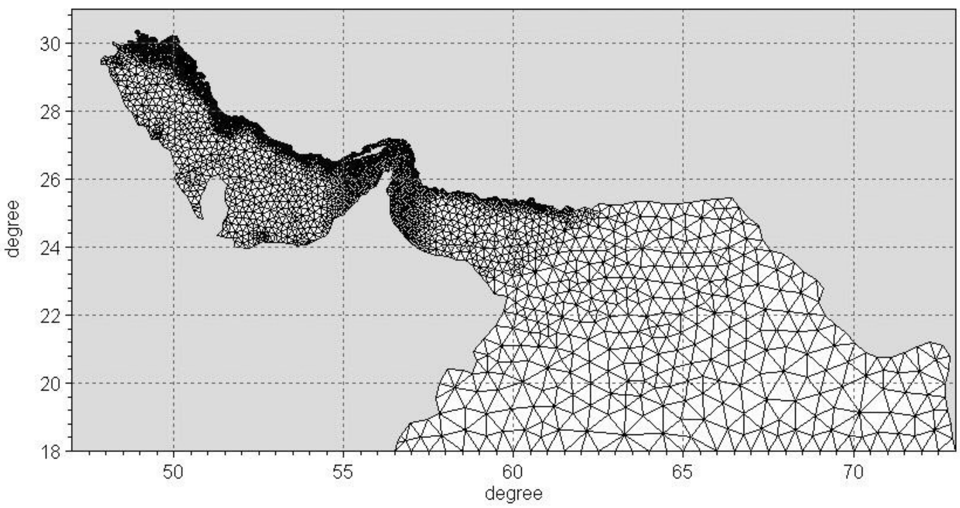

Fig. 2- Unstructured mesh and open boundary on 18° N

3- Validation data

Both input and output data are supposed to be validated against accurate measured data. Although we tried to choose the best available wind field and model set-up, input data and model parameters still need to be assessed and modified.

3-1- Synoptic station

Synoptic stations are meteorological stations which record different atmospheric parameters including wind speed and direction regularly every 3 hours. Regarding the length of recording data and accuracy of measurements, several stations located along Iranian coasts and inside Iranian islands were chosen for assessing the wind fields (Figure 1).

3-2- Buoy

Two buoys, whose data are used in this study, come from Islamic Republic of Iran Meteorological Organization (IRIMO) and are located in Bushehr and Chabahar. They are located in 27 and 17 m depth and have measured wave characteristics for 2~3 years discontinuously. Asaluye buoy belongs to National Iranian Oil Company (NIOC) operated for one year at 7.5 m depth, covering a few months of simulation period. The measurements; including significant wave height, mean wave direction and wave period are available hourly or at 3 hours intervals from three buoys (Figure 1). These measurements have gone through some quality controls. Observations that deviate more than 6 times the standard deviation of the monthly data from its mean, or more than 2 times the standard deviation of the monthly data from the previous observation, are identified as outliers and removed from the data.

3-3- Satellite

Sea winds and waves from Topex and QuikSCAT instruments are used for comparing with ISWM winds and waves. Topex data were obtained from World Wave Atlas (WWA) along 10 tracks (Figure 3). A series of data control tests have been developed with special emphasis on track consistency and with a fair degree of manual inspection and control. Root-Mean-Square Error (RMSE) after using calibration function has been calculated 0.30 *m* for the significant wave height comparing with in-situ data from NOAA, Norwegian Sea and South Pacific (Oceanor, 1999). The sea winds scatterometer on QuikSCAT satellite started operating in July 1999 and continues through the present. The grided QuikSCAT Level 3 data up to 2003 at a resolution of $0.25^\circ \times 0.25^\circ$ was obtained from the JPL sea winds project (http://podaac.jpl.nasa.gov/). Separate maps are provided for daily ascending and descending passes. The project requirement for wind speed and direction is 2 *m/s* RMSE for wind speeds from 3 to 20 *m/s* and 10% for wind speeds up to 30 *m/s* and 20° for wind speeds from 3 to 30 *m/s*, respectively (Podaac, 2001). Three versions of QuikSCAT/SeaWinds wind data (L2B, DIRTH, RSS) were collocated with buoy observations operated by the National Data Buoy Center (NDBC), Tropical Atmosphere Ocean (TAO), as well as, Pilot Research Moored Array in the Tropical Atlantic (PIRATA) project, and the Japan Meteorological Agency (JMA). According to Ebuchi et al. (2002), wind speeds and directions observed by QuikSCAT agree well with the buoy data. The RMSE of the wind speed and direction are 1.01 *m/s* and 25°, respectively.

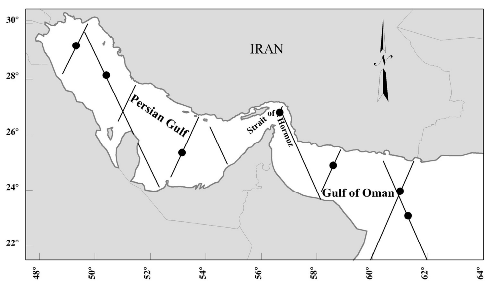

Fig. 3- Topex tracks in the Persian Gulf and the Gulf of Oman

4- Validation of ISWM

While ECMWF wind field shows generally good agreement with offshore synoptic stations and satellite measurements, coastline wind speeds are underestimated due to the rectangular land-sea mask which is used in ECMWF atmospheric model. Comparative time series and exceedence diagrams have been drawn for several points and data assimilation and increasing factors were applied at limited points. For best usage of assimilated data, ECMWF wind field is interpolated into 3 hours time step and synoptic measurements are assimilated into background wind field. Regarding non-homogeneity of data specially caused by changing the model grid spacing from 0.56° to 0.35° in Nov. 2000, time dependent factors are applied in the Strait of Hormuz. On the other hand, wave boundary condition on 18° N is underestimated at the time of tropical cyclones coming from the Indian Ocean and is modified by performing a supplementary model. Such deficiency also exists in the NCEP/NCAR reanalysis surface winds over the equatorial Indian Ocean (Goswami and Sengupta, 2003). Thus, wind fields are generated for individual cyclones from 1992 to 2002 and the cyclone modeling covering additional area from 10° N to 18° N is performed using ECMWF parametric wave data on 10° N (Figure 4). Then, the spectral wave data on 18° N are extracted from a supplementary model and merged into the spectral boundary condition for the main model. The main model is calibrated in selected periods and after an 11-year wave simulation, the output is evaluated against validation data. Cyclone simulation is not limited to a continuous hindcast period, but is also extended to 30 years from 1975 to 2004. EVA results of individual cyclones, which are of great importance, are discussed in next parts.

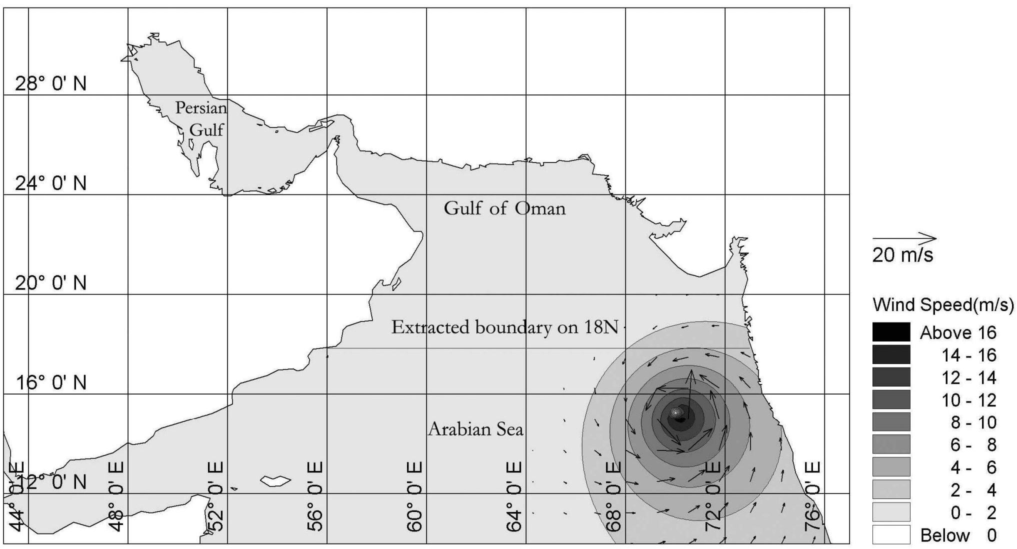

Fig. 4- Supplementary modeling area for cyclone periods

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Figure 5 shows typical time series of significant wave height (Hs) and Mean Wave Direction (MWD) for Bushehr and Chabahar buoys in the Persian Gulf and the Gulf of Oman, respectively. Recorded data are not simultaneous; therefore time series do not cover the same period.

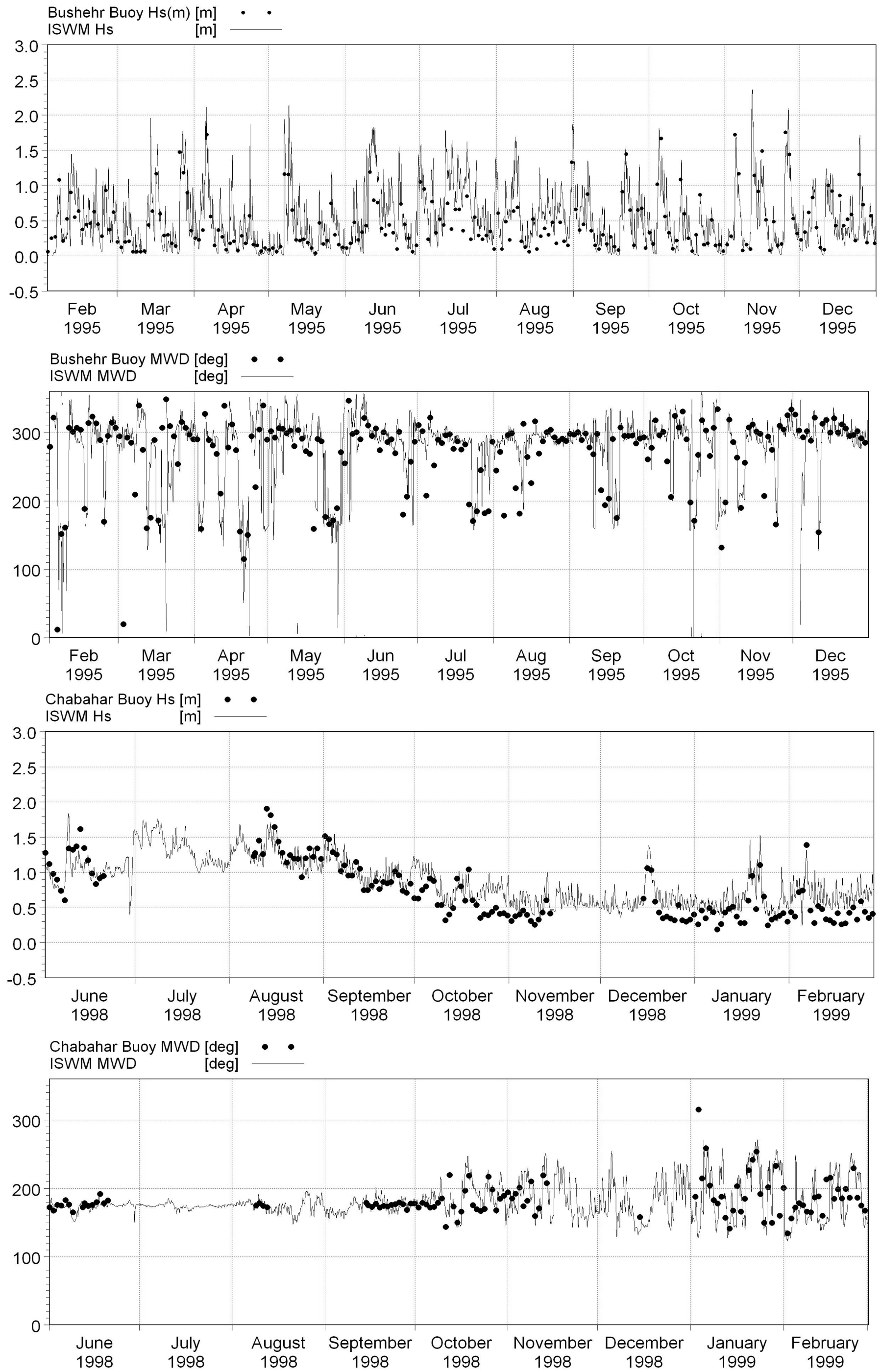

Fig. 5- Comparison of ISWM results versus buoys

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These time series describe different wave climates in these basins. A large variation of wave height in Bushehr station implies dominance of wind-waves in the Persian Gulf in all seasons. In contrast, seasonal variation of wave climate in Chabahar station is quite clear. Wave height in summer period is relatively high with a constant direction because of southwestern monsoon. The only sharp peak of Hs in this period is generated by a tropical cyclone dated 1~9 June 1998. Wave climate in the Gulf of Oman shows a different pattern in winter season. Wave height and direction from October to February is influenced by the local winds rather than swells. In general, simulated Hs tracks the buoy observation. However typically, the lowest waves tend to be slightly overestimated.

The differences between ISWM wave height product and the observations are also quantified by computing some standard statistics such as Bias, RMSE, Scatter Index (SI), and Correlation Coefficient (CC).

$$Bias = \bar{y} - \bar{x} \qquad (1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum (y_i - x_i)^2} \qquad (2)$$

$$SI = \frac{\sqrt{\frac{1}{n}\sum \left((y_i - \bar{y}) - (x_i - \bar{x})\right)^2}}{\bar{x}} \qquad (3)$$

$$CC = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \qquad (4)$$

In all these formulae, the x_i's represent the observation, the y_i's represent the ISWM product, $\bar{x}$ and $\bar{y}$ are the average and n is the number of observations.

A global view of the wave quality can be obtained by comparing the ISWM wave data with buoy data in Iranian coasts and several satellite points along Topex tracks in the Persian Gulf and the Gulf of Oman. Standard statistics have been calculated for all data and for higher waves (Hs>0.5 *m*) in Table 2. Since a wide range of values have been obtained in different projects, two well-known references from Cox and Swail (2001) in Global Reanalysis of Ocean Waves (GROW) based on NCEP/NCAR wind fields, and Caires et al. (2002) in ERA-40 project are considered for comparison. All the derived values are within the acceptable range and the ISWM accuracy increases by moving toward higher wave heights in nearshore locations.

Another parameter, which is used specifically in this project, is the Average Relative Error (Liu and Frigaard, 2001).

$$ARE(\%) = \frac{1}{n}\sum \frac{|y_i - x_i|}{x_i} \times 100 \qquad (5)$$

Table 2-Eror values in ISWM project

Error value	Buoys in nearshore		Satellites in offshore		Range from Cox and Swail (2001) for wave height in GROW	Range from Caires et al. (2002) for wave height in ERA-40
	All wave heights	Wave heights > 0.5 *m*	All wave heights	Wave heights > 0.5 *m*		
Bias (m)	0.06	0.04	-0.07	-0.10	-0.32 – 0.85	-0.44 – -0.02
RMSE (m)	0.22	0.24	0.35	0.38	n/a	0.31 – 0.71
CC	0.86	0.71	0.85	0.83	0.67 – 0.93	0.82 –0.95
SI	0.39	0.25	0.40	0.30	0.17 - 0.60	0.13 – 0.32

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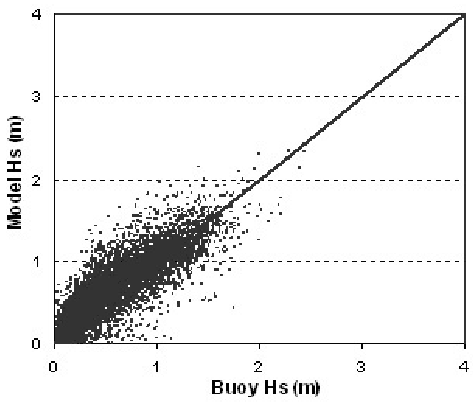
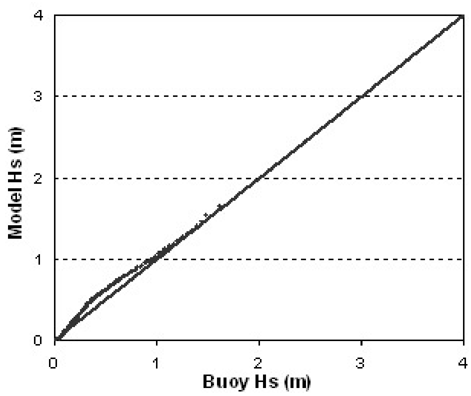
Due to the importance of simulation of big waves, especially for the EVA which is part of this study, this parameter has been calculated for waves higher than 1 *m*. ARE is 12% for nearshore locations and 19% for satellite offshore that shows good agreement between model and measurements. ARE is reduced to 8% and 18%, in nearshore and offshore respectively, for waves higher than 1.5 *m*. The scatter plots and quantile plots help visualizing the differences and deficiencies of the data set. Figure 6 shows excellent agreement between buoys and ISWM wave heights. As it was shown in buoy comparison, there is a tendency in nearshore output to overpredict slightly the lowest sea states. The same feature exists in GROW and ERA-15 projects (Cox and Swail, 2001).



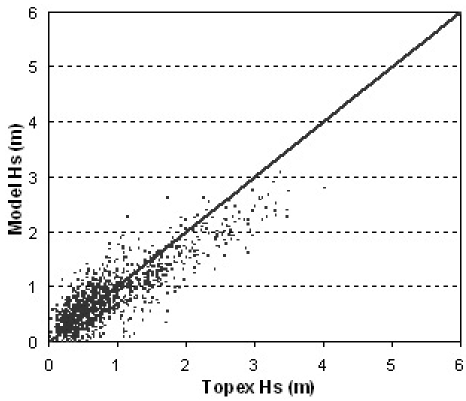
(a)



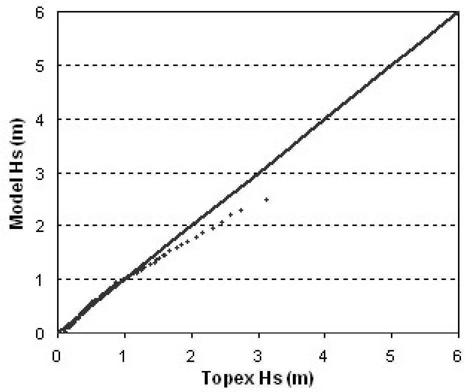
(b)

Fig. 6- Scattering (a) and quantile (from 1 to 99%, b) wave height (m) comparisons of ISWM and buoy measurements

Figure 7 shows the scatter and quantile plots of the Topex significant wave height observations and the corresponding ISWM data on more than 1600 wave records over 7 points in Figure 3. The ISWM underestimates some of the high peaks of the significant wave height and shows good correspondence with the observations at low sea states. It was quite predictable from negative bias in satellite which is decreasing by moving toward higher wave heights. Negative bias implies that the average of modeled values is smaller than measured ones.



(a)



(b)

Fig. 7- Scattering (a) and quantile (from 1 to 99%, b) wave height (m) comparisons of ISWM and Topex measurements

It should be noted that the wind field modification and the model tuning were performed to capture the best results in Iranian coastline. This procedure has produced a good agreement for Iranian nearshore locations, but the accuracy is unknown for other coasts. This deficiency can be treated using wind and wave measurements of southern coastlines in model tuning and performance in future and the ISWM results would be hopefully an invaluable source for regional coastal engineering and management.

5- EVA Results and discussion

Long term wind and wave characteristics for 5, 20, 50 and 100 years return periods are calculated based on fitting a theoretical probability density function to the observed extreme value series. Different distribution functions and fitting methods are evaluated to find the risk of extreme events in the study area. Truncated Gumbel shows the best goodness of fit statistic, less standard deviation in uncertainty calculations and smooth spatial pattern for both wind speed and wave height. Figure 8 shows 100-year wave height and standard deviation of simulated values with Monte Carlo method in the output area. Details of distribution and simulation method are provided in Appendix A.

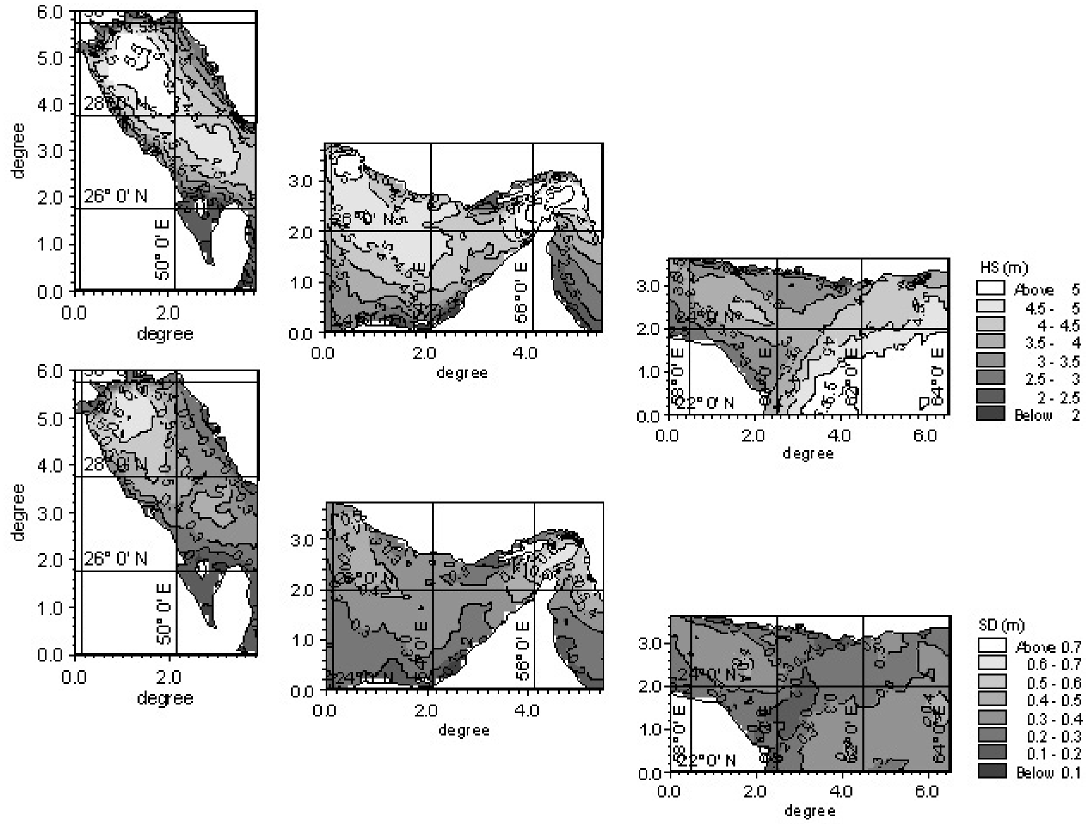


Fig. 8- 100-year Hs (top) and corresponding standard deviation (bot.) in the Persian Gulf and the Gulf of Oman based on an 11- year continuous wave hindcast

There are recommendations such as 15 or 30 years data to have a reliable 100 year wave height estimate, but there is no specific work or paper regarding the minimum length of storm wave data for estimating the design wave height with the return period of 100 years or so. It is well known that the width of confidence interval of the 100 year wave height decreases with the increase in the data length and the number of storm events (Goda, personal communication). Therefore, it is recommended to consider a range of wave height (i.e. $Hs \pm 2\times$Standard deviation) rather than a single value for 100 years return period.

Similar analysis was performed on 41 individual simulated cyclones, occurred between 1975 and 2004 in the Gulf of Oman. According to Figure 9, maximum 100-year wave height increases from 5.5 to 8 *m* while there is a slight decrease in wave height in Iranian coasts. Therefore, EVA results of cyclone modeling in offshore area are assimilated into the main data base, derived from 11-years simulation.

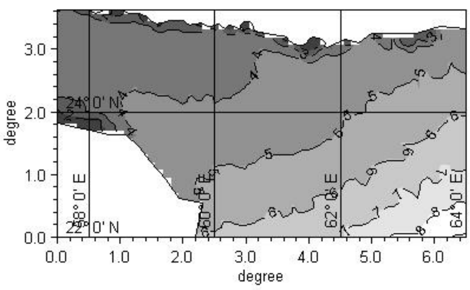


Fig. 9- 100-year Hs in the Gulf of Oman based on a 30-year individual cyclone simulation

Extreme calculation is verified by means of EVA analysis on available measurements. Satellite data from Topex cover the study area in hindcast period, but 10 days time step for data recording does not provide an appropriate wave field for extreme calculations. Thus, Extreme values are calculated on buoys measurements and corresponding values are obtained from the model. Bushehr and Chabahar buoys with a minimum of two years of recording data are selected for comparisons. Table 3 shows EVA results from recorded and simulated data as well as correlation coefficient between extracted values and corresponding values from truncated Gumbel distribution. Coefficients are satisfactory for fitness of selected distribution to extreme data.

Extreme values would be more applicable in engineering if directions of coming wind and wave in different return periods are specified. The results would be helpful for engineering purposes such as optimizing marine structures layout, design and construction. This demand was met by dividing wind and wave data into eight 45° directions. Figure 10 shows 100-year wave height in dominant directions in the Persian Gulf and the Gulf of Oman with special attention to Iranian coasts. It is interesting to know that all values from directional analysis are smaller than values from non-directional analysis. Wave height in dominant directions e.g. North West, West and South East directions which are shown in this Figure are at most equal to wave height in non-directional analysis given in Figures 8 and 9.

Table 3- Comparison between EVA results from buoys and ISWM data

Location Parameter	Bushehr Buoy	Bushehr ISWM	Chabahar Buoy	Chabahar ISWM
2-year Hs(m)	2.47	2.29	1.95	2.03
5-year Hs(m)	2.65	2.42	2.03	2.17
10-year Hs(m)	2.77	2.51	2.08	2.27
CC	0.98	0.98	0.93	0.95

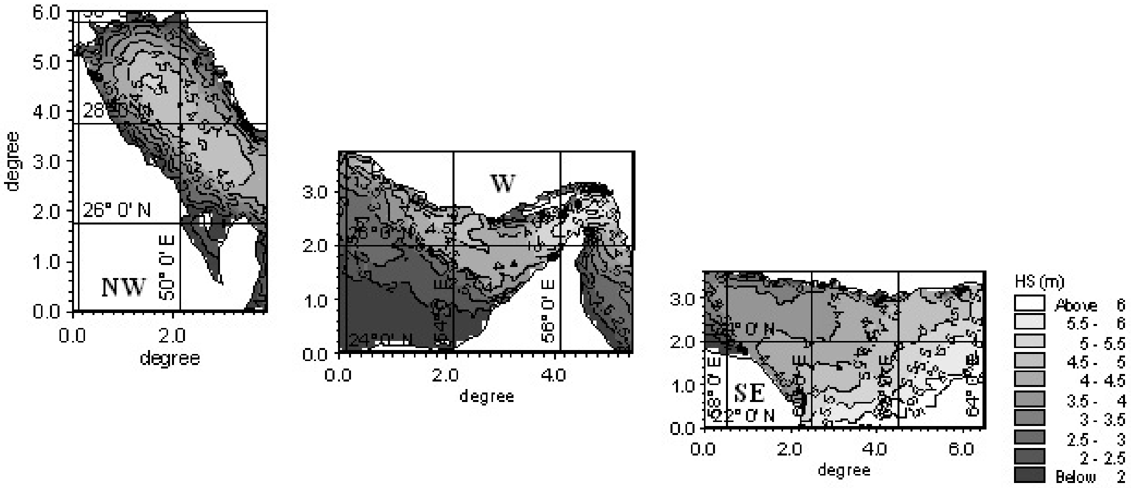


Fig. 10- 100-year Hs in the Persian Gulf and the Gulf of Oman in dominant directions

6- Derivative products

The main product of ISWM consists of a sophisticated GIS-based program called Iranian Wave Atlas (IWA) which covers all the results of the simulation in the Persian Gulf and the Gulf of Oman (Figure 3). IWA is a comprehensive database for engineering and environmental purposes. This program provides wave parameters including significant wave height (Hs), wave periods (Peak wave period and T_{02}), mean wave direction for swells, wind waves and total waves separately, as well as wind speed/direction in each point, using on-line display position (lat/long) of the pointer. Parametric data are provided up to 5 meters depth at 0.125 degree spatial resolution and 6 hours temporal resolution and the wind and wave EVA results are available at the same points. The wave energy spectra are archived at 0.125 degree resolution for nearshore and 0.25 degree resolution for offshore areas. Many statistical parameters such as minimum, maximum, average, monthly and quarterly average, frequency and probability density can be easily calculated for each point/parameter in IWA program. Wind and wave rose also can be drawn in this program. It should be mentioned that IWA consists of the wave modeling results in the Caspian Sea that is not discussed in this paper.

Figure 11 shows the interface of IWA software. Users can view geographical information of the grid points on the map. Data can be uploaded by selecting points and extracting time series. Simple statistical analysis can also be executed in this software. Explanations about each button are given in the help of software.

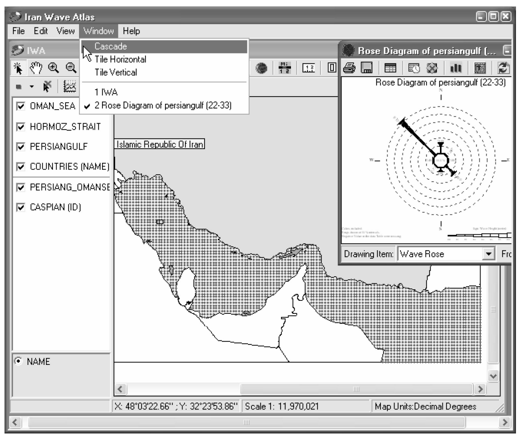


Fig. 11- A view of IWA software

7- Conclusions

The ISWM project has successfully generated a comprehensive set of wave data for the Persian Gulf and the Gulf of Oman basins for an 11-year continuous period (1992-2002) and 41 storms of various dates between 1975 and 2004 in the Gulf of Oman.

- The approach is based on driving modified operational ECMWF wind field over the whole basins. Open boundary of the Gulf of Oman was obtained from the same center and the big swells generated by cyclones were assimilated in the observed time by the satellite with the appropriate strength. Tuning was generally performed for Iranian coasts and the offshore area and southern coasts were at lower interest.
- The statistical parameters show good agreement between ISWM results and validation data especially in term of bias. All the parameters have been compared with the values derived from reference global hindcasts and are in acceptable range.
- ISWM results show excellent agreement with nearshore measurements in Iranian coasts, but the offshore data are a bit underestimated for big waves.
- Test runs and related investigations in EVA show that the most appropriate statistical distribution for both wind and wave is truncated Gumbel. The wind speed and wave height over the two basins have been calculated for 5, 20, 50 and 100 years return periods. The 30-year cyclones in the Gulf of Oman are considered in the EVA and have shown strong effect in the offshore area.
- Directional EVA results do not exceed non-directional values in these basins and provide an applicable data source for economic marine design.
- The research output which is accessible via IWA program will prove invaluable for design and operational purposes and environmental managements. The results can be evaluated against new altimeter and in-situ observations. Although satisfactory results are obtained at this stage, accuracy can be improved by carrying out a local wind modeling and higher resolution wave hindcast. Wave forecasting can be added to future project as well.

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Appendix A

Gumbel Distribution

The Gumbel distribution is given as

$$f(x)=\frac{1}{\alpha}\exp[-\frac{x-\zeta}{\alpha}-\exp(-\frac{x-\zeta}{\alpha})] \qquad \text{(A.1)}$$

$$F(x)=\exp[-\exp(-\frac{x-\zeta}{\alpha})] \qquad \text{(A.2)}$$

Where f(x) is the probability density function and F(x) is the cumulative distribution function or the probability of non-exceedance, ζ is location parameter and α the scale parameter.

A truncated Gumbel distribution for modeling exceedances above the threshold level x_0 can be defined by g(x) and G(x) as probability density function and cumulative distribution function.

$$g(x) = \frac{f(x)}{1 - F(x_0)} \qquad (A.3)$$

$$G(x) = \frac{f(x) - f(x_0)}{1 - F(x_0)} \qquad (A.4)$$

Monte Carlo Simulation

In Monte Carlo Simulation the standard deviation is obtained by randomly generating a large number of samples that has the same statistical characteristics as the observed samples. The algorithm can be summarized as follow

1. Randomly generate a set of m data points from considered distribution using the estimated parameters, i.e.

   $$x_i = F^{-1}(r_i, \theta) \qquad i = 1,2,3,\ldots,m \quad (A.5)$$

   Where r_i is a random generated number between 0 and 1, θ is calculated parameters for distribution such as location and scale, m is equal to sample size used in extreme analysis before. Then, wave height for selected return period (x_t for t years) is calculated for m data.
2. Step 1 will be repeated k times. The standard deviation s_t of the T-year event estimate are then given by

   $$s_t^2 = \frac{1}{k}\sum_{j=1}^{k}(x_t^{(j)} - \bar{x}_t)^2 \qquad (A.6)$$

Investigations suggest that Monte Carlo based estimates of mean and standard deviation of the T-year event estimator saturate at sample size in the order of k=10000.

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