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Integration of geographical information system and Wave Hindcast model - case study: Persian Gulf

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ABSTRACT

In this study, a numerical third-generation wave model was performed to generate 10 years (2000-2010) of wave hindcast in the Persian Gulf. The modified wind field data of European Center for Medium Range Weather Forecasts (ECMWF) and bathymetry data were used as the input data to model. In situ measurements and satellite-derived wave height were performed for model calibration, and validation the results. The results show that the overall accuracy is more than 80% over the whole Persian Gulf. Geographical Information System (GIS) was used to handle all datasets through a user-friendly software which provides required tools for data visualization and manipulation. Data management was carried on using the integration of Relational Database Management Systems (RDBMS) and GIS components.

1. Introduction

Persian Gulf is a semi-enclosed marginal sea in a typical arid zone and it connects to the Indian Ocean through the Strait of Hurmuz. The gulf is 990km long and its width ranges from 56 to 340 km. Its total volume is 7000–8400 km3 of seawater [1, 2]. The most area of basin lies upon the continental shelf [3]. The average water depth is 35.0 m, and some locations with depths more than 107m were observed. The depth increases from south toward the northeast. Geopolitically and economically Persian Gulf is one of the most pathways in the world.

Long term data of sea waves are very essential from safety and economic point of view for such projects [4]. The lack of adequate information on the physical and environmental characteristics of sea state will be pretend either in an unsafe structure or with an over-designed structure in this region [5]. In the study area, there is no long-term wave datasets which are essential for design of coastal structures. In practice, the modeled hindcast wave data is usually used for such purposes. Since 1980s, several professional numerical models have been developed for weather prediction and sea wave modeling by international agencies (i.e., U.S. Navy Fleet Numerical Meteorology and Oceanography Center, U.S. National Center for Environmental Prediction, U.S. Navy Operational Global Atmospheric Prediction and European Center for Medium-Range Weather Forecasts). Nowadays, sophisticated wave models are run at many meteorological centers in the world, and also dedicated long term hind-casts have been performed [6, 7, 8, 9, 10]. Although Met-Ocean datasets are freely available in global scales by these agencies, spatial and temporal high resolution regional datasets and numerical models are required for coastal engineering and environmental purposes [11].

However, to get a reliable understanding of the wave climate in the Persian Gulf, few wave hindcast study have been performed locally or over the whole gulf. EL-GINDY and HEGAZI [3] provided a hydrographic atlas for the Persian Gulf and Oman Sea. However, they focused on the tidal and density driven currents. Also, another oceanographic atlas has been developed by AL-YAMANI et al. [12], which provides valuable oceanic datasets around the Kuwaiti territorial waters. This atlas does not cover the whole Persian Gulf, and also does not cover the complete hydrodynamic characteristics of the Kuwaiti territorial waters. A comprehensive met-ocean model of the Persian Gulf (PERGOS) has been developed by DHI Water and Environment together with Ocean Weather Inc for the whole Persian Gulf. The wind and wave hindcast datasets were modeled in PERGOS in basin-wide grids of spacing 0.0625 degrees in latitude and longitude (7 km) nested within coarser grid systems. Two-dimensional surge, tide, and currents have been simulated in this atlas using DHI's MIKE 21 using a mesh resolution less than 7 km. The datasets available for a period of 20 years from 1983 [www.dhigroup.dk]. PERGOS is just commercially available and cannot be distributed freely. In addition, it does not available through a user-friendly digital atlas, and users have to purchase the DHI's commercial softwares to use the results of PERGOS.

Rakha et al. [5] have developed a hydrodynamic atlas for the Persian Gulf. They have used the WAM and RMA-10 models for their simulation. It is a good challenge at the end of this paper to compare the results of Rakha et al. [5] with our results, because different models and basic data have been implemented. Other centers have also generated similar data for the Persian Gulf. However, these datasets are available in coarse grids that do not provide adequate and reliable data for coastal engineering application [13, 14, 8, 5].

Such as of many other oceanic phenomena, knowledge of wave climate and its application in marine engineering needs data and information. At the technical level, integrated management of the ocean and seas relies on two basic tools: Modeling & Data [4]. Modeling acts as a tool so that the environment modeling-decision making relationship is developed as a bridge between scientific research and policy analysis. However, availability of raw and modeled data is not a sufficient condition to produce the required information about the oceans and seas. It is the utility or usefulness of data that contributes to production of information. Transfer of wave modeled data into information involves several activities such as spectral, Statistical, spatial and temporal analysis [15]. Each of these activities contributes to retrieval of the required information from raw data. Spatial nature, large volume and organization of wave modeled data and information are the most important aspects in the sea wave data management and visualization that directly support the good decision making for coastal engineering application of these datasets. However, through the use of Geographical Information System (GIS) and the associated software; these data can be managed, compiled, and processed. Integration of GIS with wave hindcast datasets accomplish a number of significant functions such as: manipulation, modifying, data analysis and visualization [16]. GIS improves the ability to incorporate spatial details beyond the existing capability of numerical models [17].

This paper describes the methodology and general approaches toward the wave hindcast in the Persian Gulf. The first attempt began by deploying some wave measurement stations, and other data sources such as satellite data and results of the other regional and large-scale numerical models. In this study a third-generation wind driven wave model is used to model the wind waves. A 10-year database is generated from 1st January, 2000 till 31st December, 2010. Modeled data were tuned using measured data and thus the data provided by the models can be used with confidence. In this study, all generated data are converted as a geographic database schema, and we aim to generate an interactive hydrodynamic atlas. Here, we aim to present a methodology for data management and application of the modeled sea wave datasets using GIS.

2. Data and methods

Equations start from the far left of the row. They are numbered consecutively. The equation numbers must be bracketed and placed opposite to the equation on the far right of the line.

The bathymetric data, satellite data, wind fields and the results of wave hindcast data have been used in this study [Table 1]. The bathymetry data were compiled from the combination of Mike C-Map [18] and hydrographic charts after a QC check [Figure 1a]. Wind data were gathered from operational ECMWF with a reasonable spatial resolution required for this study. In situ measurements obtained from weather synoptic stations and buoys, and satellite-derived wave data were used for data validation after a QC check. Details of these datasets have been shown in Figure 1b and Table 2.

In this study, Mike 21 spectral wave model SW, a third-generation spectral wind-wave model based on unstructured meshes [18], has been used. This model uses the wind fields for simulation of wind generated waves and swells in offshore and coastal areas. The wind-wave interaction (generation), wave-wave interaction (quadruplet), dissipation and bottom friction physical processes are included in the model. The model was setup for the entire Persian Gulf with a grid spacing of 0.125 degree. The output of model was utilized in 16 directions, 25 frequency bands, and a time step of 900 seconds.

3. Results

The quality and accuracy of wind data directly influence the results of any numerical wave hindcast models [19, 11]. For example, in an open ocean area, wave height approximately corresponds with the wind speed by a square factor [20]. Therefore, the accuracy of wind data is the most important key in the wave hindcast study. ECMWF wind field showed relatively good agreement with in situ measurements in the offshore regions, and with satellite measurements. In contrast, wind speeds at coastal areas were underestimated due to the rectangular land-sea mask and corresponding surface roughness along coastlines of the Persian Gulf [Figure 2a, b]. The exceedance diagrams of some coastal selected points from ECMWF wind data showed underestimate shift in comparison with in situ and satellite measurements [Figure 2c]. Here, wind field data were optimized by transferring data from offshore grids to the nearshore grids without any interpolation or extrapolation, and as well as by performing an increasing factor [20]. The results of this procedure revealed a good correlation of wind field data with in situ and satellite measurements [Figure 2d].

Table 1. Specification of datasets used in this study

Group	Database	Provider	Resolution	Limitation	Implementation Status	Ref
Bathymetric Data	Admiralty maps	UKHO	Sc: 1/150.000 – 1/50.000	No full coverage	Complementary XYZ data*	Fig 1
	Mike C-Map	DHI	Sc: 1/150.000 (C level)	No more high resolution	reference for bathymetry data	
	NCC Maps	NCC	Sc: 1/25000, 1/100.000	No full coverage	Complementary XYZ data	
	NGC Maps	NGC	Sc: 1/25000 – 1/100.000	No full coverage	Complementary XYZ data	
Wind Fields	ECMWF	ECMWF	S: 0.5 X 0.5, T: 3 h	Needs modification at coastal area	reference for wind field data	
	NCEP/NCAR	NCEP	S: 2.5 X 2.5, T: 6 h	Spatial resolution is coarse	Used for model validation	
	UKMO	OCEANOR	S: 1.25X0.833, T: 6 h	No full temporal coverage	Used for model validation	
In situ data	Synoptic Stations	IRIMO	T: 3 h	No continuous recorded, needs QC	Used for model validation	Fig 1, Table 2
	Buoy data	IRIMO, PSO, NIOC	Not unique for all stations	No continuous recorded, needs QC	Used for model validation	
Satellite data	Sat. altimetry+	AVISO / NASA	T: 10 days	Temporal resolution is too coarse	Used for model validation	Fig 1
	Quick Scat	NASA	S: 0.25X0.25, T: 4 days	Temporal resolution is too coarse	Used for model validation	
Wave modeled data	Persian Gulf Hydrodynamic Atlas	Rakha et al. (2007)	S: 0.1 X 0.1 T: 300 sec	no source data available	Results used for comparison	
	PERGOS	DHI	S: 0.0625, T: 6 h	Commercial license only	Demo version used	

+: Topex/Poseidon and Jason-1 along track Wave height and Wind Speed girded data

Avb: Availability (in the final Atlas database)

Ref: Reference (in this paper)

DHI: DHI water & Environment

NCC: National Cartography Center of Iran

NGC: National Geographic Center of Iran

PSO: Ports and Shipping Organization of Iran

NIOC: National Iranian Oil Company

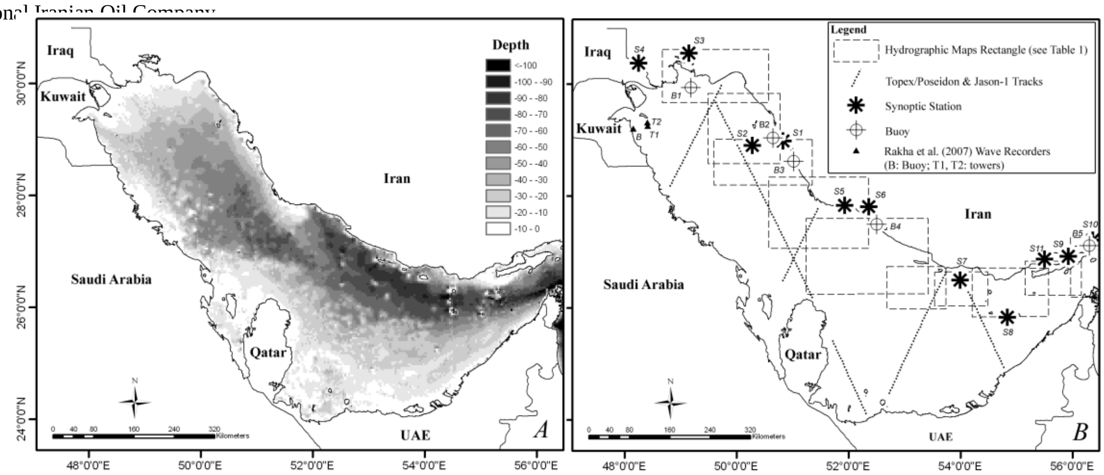


Figure 1. (a): Bathymetry map, (b): Basic datasets used in this study. Refer to Table 1 & 2.

Table 2. Details of the in-situ measurements used in this study

Category	Label in fig 1	Period	Lon	Lat	Elev./Depth	Measured Parameters
Synoptic Station	S1	2000-2010	50.83	28.98	+19.6	Wind Speed Wind Direction
	S2	2000-2010	50.82	28.90	+8.4	
	S3	2000-2010	49.15	30.55	+6.2	
	S4	2000-2005	48.25	30.37	+6.0	
	S5	2000-2006	51.93	27.83	+4.0	
	S6	2000-2010	52.36	27.81	+6.5	
	S7	2000-2010	53.99	26.50	+30	
	S8	2000-2008	54.83	25.83	+6.0	
	S9	2004-2006	55.92	26.93	+6.0	
	S10	2000-2008	56.36	27.21	+10.0	
	S11	2000-2010	55.30	26.76	+5.2	
Buoys	B1	2010	49.18	29.93	-17.0	Hs, Tz, Tp
	B2	2000-2008	50.65	29.04	-15.0	Hs, MWD
	B3	2000-2005	50.70	28.91	-27	Hs, Tp, Tz, MWD*, T01, T02
	B4	2000-2006	52.50	27.59	-7.5	Hs, MWD*, Tz, Tp
	B5	2000	56.29	27.11	-5.2	Hs, Tz, Tp
Rakha et al. (2007) observations	B	1994-2006	-	-	-	Wave height and period (time series graph available)
	T1	1994-2006	-	-	-	
	T2	1994-2006	-	-	-	

*MWD: Mean Wave Direction

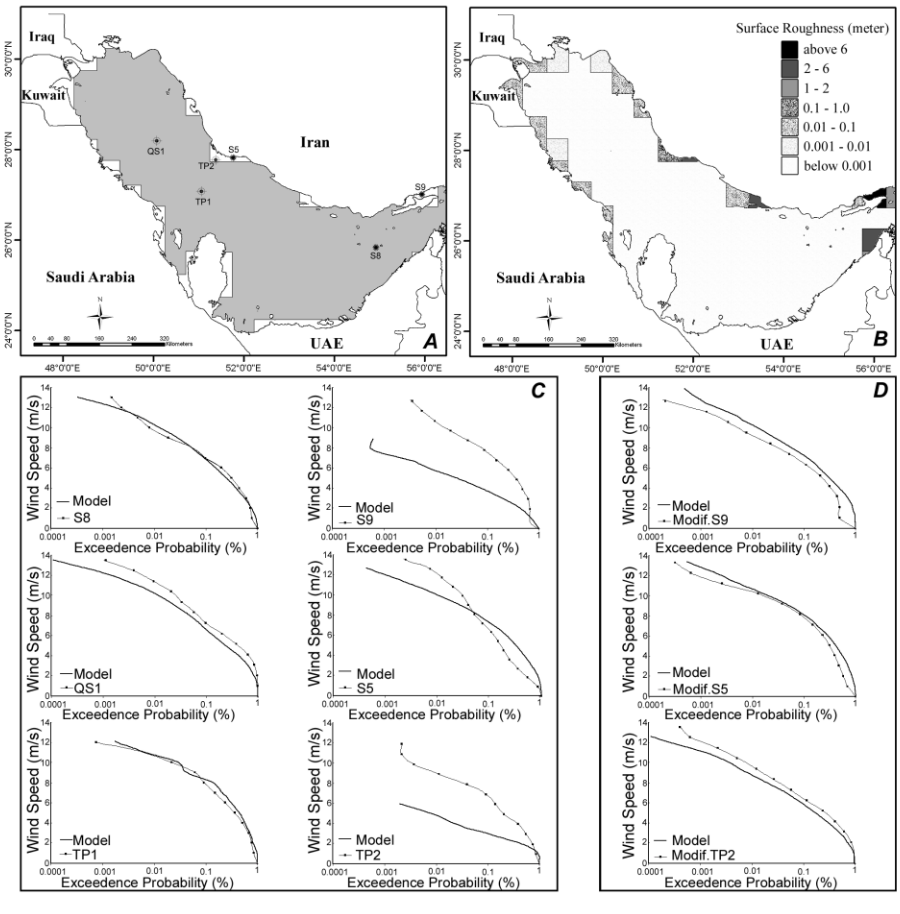


Figure 2. (a): Land mask, and (b): Surface roughness of ECMWF-Operational over the Persian Gulf. (c): Exceedence probability plots of in situ and satellite measurements (TP1, TP2: Topex/Poseidon; QS1: Quick scat). For details of the stations refer to Table 2. (d): Exceedence probability plots of Figure C after ECMWF data transformation based on Weisse and Feser (2003) method.

The wave model was calibrated using in situ wave measurements from Iranian territorial waters [Figure 1]. The wave height of storm events was under-prediction in the model results. The regression analysis was performed for modification of waves exceeding 0.5m in height. The corrected outputs were evaluated using in situ measurements and satellite data. Fig 3 shows typical time-series of Significant Wave Height (Hs), zero-crossing period (TZ) and mean wave direction (MWD) for buoys established in the Iranian coastal areas. Table 3 shows the statistical parameters of all modeled data and higher waves (Hs > 0.5 m). It is observed that the model predicts the wave parameters very well. However, Statistical results were compared with the two well-known references from Cox and Swail [21] in Global reanalysis of Ocean Waves (GROW) based on NCEP/NCAR wind fields, and Caires et al. [22] in ERA-40 project. This comparison shows that all the derived values are within the acceptable range for both offshore and nearshore data. Scatter plots are very suitable for assessment of the results. These plots help to visualize the difference and deficiency of datasets. Figure 4 shows the scatter plots of the model results and the in situ and satellite measurements. The simulated data shows a good agreement with the observations at low sea state, while some peaks are slightly underestimated in offshore area. To present the accuracy of the model, the Average Relative Error (ARE) [23] were calculated for all data and for higher waves (Hs > 0.5 m) [Table 4] in nearshore and offshore locations [Table 4]. The results show that the overall accuracy is more than 80% for all simulated data, and the waves with Hs>0.5m show higher accuracy over the whole Persian Gulf.

In order to get the best results from the model, the output files are needed to be converted into diagrams or graphs so that the interpretation and the comparison of different datasets can be achieved easily, which is a way of checking the accuracy of the simulation. The integration of numerical modeling and Geographical Information System (GIS) recently evolved from a relationship of mere exchanging of output files to more intimate integration [24]. In this study, integration consists of having GIS capabilities and full datasets of observed and modeled data through an object-oriented GIS-based user friendly software, which is the main product of this study, and called Iran Wave Atlas (IWA). IWA covers all the results of the wave simulation and provides a comprehensive geodatabase of specification of full range of normal and extreme wind and wave design data required engineering and environmental processes on the scale of grid systems adopted. The ESRI's commercial software component called ArcObject has been used for programming in IWA development, which provides the GIS capability for this software [24]. IWA uses the ArcMarine Data model [25] for its database and relating it to the GIS component.

The main outputs of the model in this study are time-varying quantities of scalar and vector values. The vector and scalar quantity tables further define the mesh points so that data have been stored depending on its scalar or vector nature, respectively. IWA is able to relate these data with the spatial objects performing the grid cells and measuring points through the object oriented classes related to the geodatabase. The various parameter objects such as wave height, wave period, and wind speed were designed as a lookup table for all parameter which have been stored in the geodatabase. The parameter table stores basic attributes describing the parameters. Time-series value of each parameter also stored in the scalar and vector quantity tables which could be accessed in relation to the parameters table. These tables can be approached in various ways. When users query the table or spatial objects for a specific parameter or a geographic location, access is provided through the relationship classes to the actual time-series values. Likewise, when investigating specific features and data values, the same set of relationship classes provides access to the parameter table and to information describing the data values [Figure 5]. The feature classes and their relationships provide several access routes to the data. The extracted data can be rendered and visualize as scalar or vector spatial display, time-series graphs, contour maps, wind and wave rose diagrams and statistical graphs. Figure 6 shows the main interface page, and some data analysis products of IWA software.

Table 3. Statistical values of hind-casted wave height in this study compared with global standards.

	Buoys		Satellite		Standard Rang	
Param.*	All	Hs>0.5	All	Hs>0.5	*	**
Bias (m)	-0.06	-0.04	0.07	0.10	-0.32 – - 0.85	-0.44 – 0.02
RMS (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

*- Cox and Swail (2001)

**- Caires et al. (2002)

4. Discussion and Conclusion

As noted above, a 3rd generation of spectral wind-wave model based on unstructured meshes has been used for 10 years (2000-2010) wave hindcast of Persian Gulf. The approaches are based on modified operational ECMWF wind field and in situ and satellite observations over the whole basin. Statistical evaluations show that the results of this study have more than 80% agreement with direct observations, and the difference between similar time-series data are noticeable low. Similar works have been done before

Table 4. Average Relative Error (ARE%) of the hind-casted wave height in the Persian Gulf.

	Compared with Buoys in Nearshore		Compared with Satellite measurements in offshore	
	All	Hs>0.5 m	All	Hs>0.5 m
ARE%	12	8	19	18

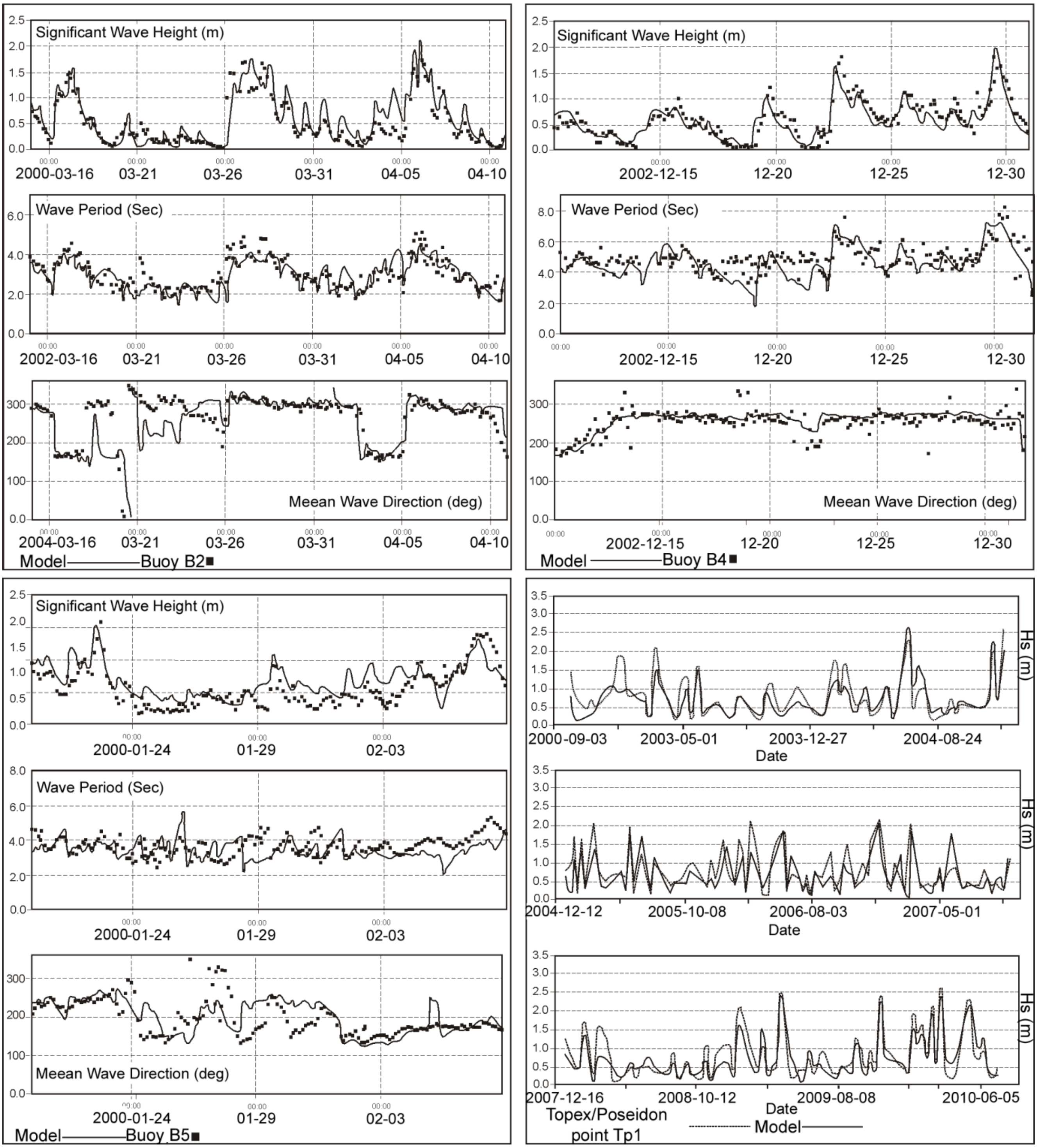


Figure 3. Time-series plots of significant wave height, wave period and mean wave direction of model and selected buoys and Satellite measurements. For details of buoys refer to the Table 2.

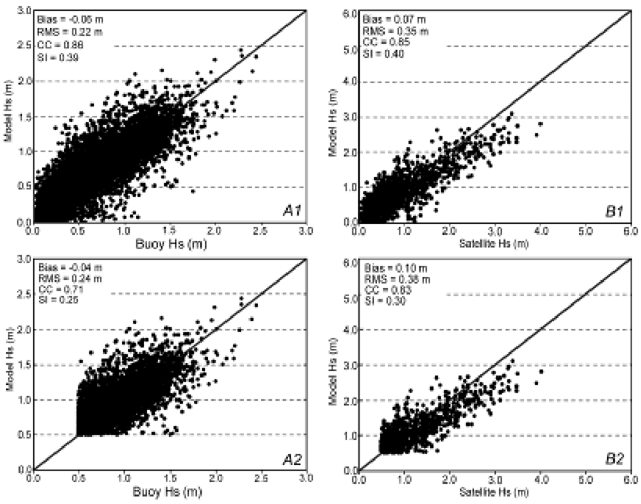
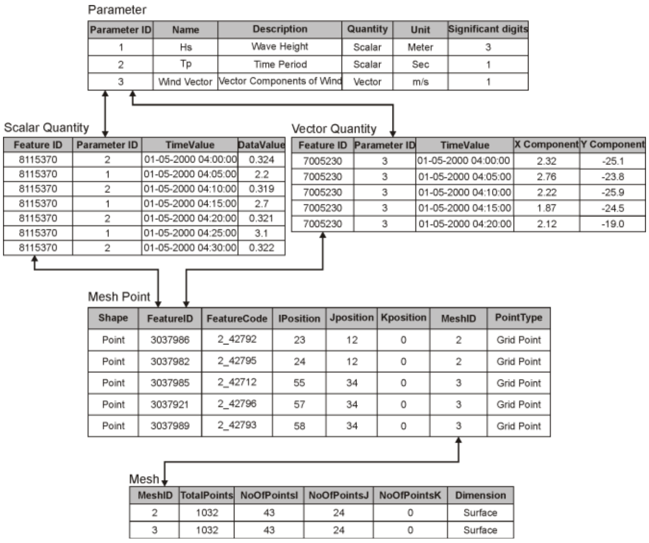


Figure 4. Scatter plots of modeled wave height versus buoys and satellite measured wave heights. A1, B1: all datasets, A2, B2: Hs > 0.5 m.

for this area [3, 5]. These studies have used 3rd generation models with different approaches to this study. Figure 7 shows the comparison of the timeseries data of this study with another available similar work [5]. However, this comparison shows that the results of these two projects are in good agreement especially at extremes, although some differences exist. Finally, it could be concluded that the 3rd generation wave hindcast models with valid and reliable wind field and other required data, can present an authentic wave climate of the Persian Gulf. Some differences between these two studies and similar another works should be due to the different approaches and also validation data applied to the models. It is strongly recommended that all adjacent countries around the Persian Gulf establish in situ measuring networks for wave and the other hydrodynamic parameters.

In order to achieve a practical and easy to use hydrodynamic database for coastal engineering applications, it is accepted that the outputs of the hydrodynamic models must be converted to information. To do this, data management systems must be considered as one of the essential parts of the hydrodynamic atlases. Available wave simulation models have irregular or commercial data formats which are not in international standards for data sharing through the operational data management systems. Hence, all datasets (basic, in situ and model results) should be converted into operational and easy to use databases. In addition, GIS is a powerful tool for data management and analysis that should be used in data management systems. Integration of GIS with relational database management systems (RDBMS) could be a good solution. This study presents a methodology for development of the wave atlas software for the Persian Gulf. The results of this study are available in this software and enable us to perform wave hindcast models and forecasting of wind and waves for this region.



Parameter

Parameter ID	Name	Description	Quantity	Unit	Significant digits
1	Hs	Wave Height	Scalar	Meter	3
2	Tp	Time Period	Scalar	Sec	1
3	Wind Vector	Vector Components of Wind	Vector	m/s	1

Scalar Quantity

Feature ID	Parameter ID	TimeValue	DataValue
8115370	2	01-05-2000 04:00:00	0.324
8115370	1	01-05-2000 04:05:00	2.2
8115370	2	01-05-2000 04:10:00	0.319
8115370	1	01-05-2000 04:15:00	2.7
8115370	2	01-05-2000 04:20:00	0.321
8115370	1	01-05-2000 04:25:00	3.1
8115370	2	01-05-2000 04:30:00	0.322

Vector Quantity

Feature ID	Parameter ID	TimeValue	X Component	Y Component
7005230	3	01-05-2000 04:00:00	2.32	-25.1
7005230	3	01-05-2000 04:05:00	2.76	-23.8
7005230	3	01-05-2000 04:10:00	2.22	-25.9
7005230	3	01-05-2000 04:15:00	1.87	-24.5
7005230	3	01-05-2000 04:20:00	2.12	-19.0

Mesh Point

Shape	FeatureID	FeatureCode	IPosition	Jposition	Kposition	MeshID	PointType
Point	3037986	2_42792	23	12	0	2	Grid Point
Point	3037982	2_42795	24	12	0	2	Grid Point
Point	3037985	2_42712	55	34	0	3	Grid Point
Point	3037921	2_42796	57	34	0	3	Grid Point
Point	3037989	2_42793	58	34	0	3	Grid Point

Mesh

MeshID	TotalPoints	NoOfPointsI	NoOfPointsJ	NoOfPointsK	Dimension
2	1032	43	24	0	Surface
3	1032	43	24	0	Surface

Figure 5. Data model structure of Iran Wave Atlas software. The structure allows users to approach the data from several conditions, either spatially by querying a Mesh for points and then determining the data available, or to find all points of a certain parameter type.

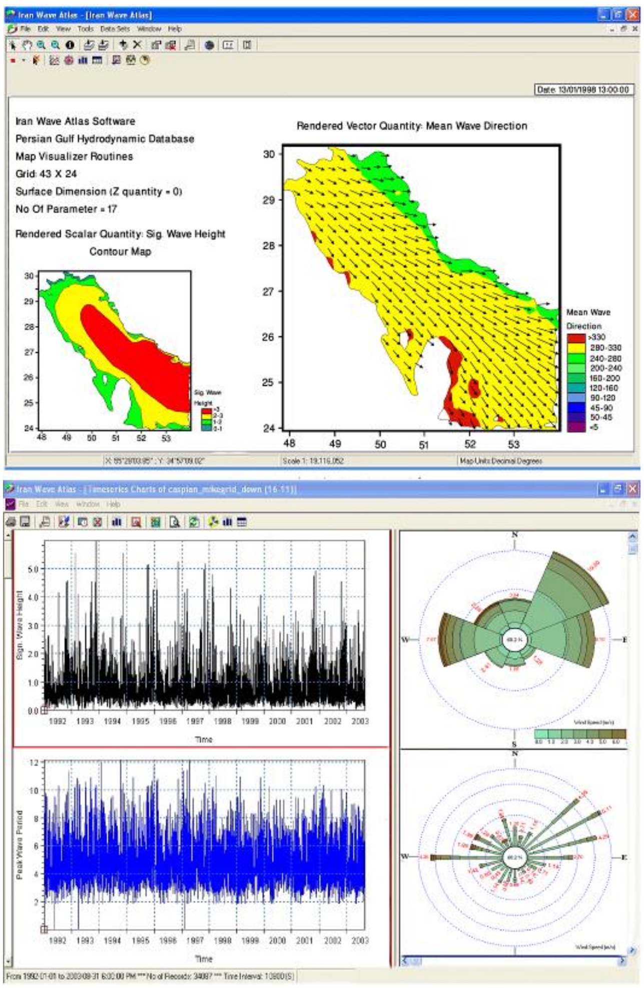


Figure 6. Screen shots of Iran Wave Atlas main page and data products page.

prediction systems at the fleet numerical

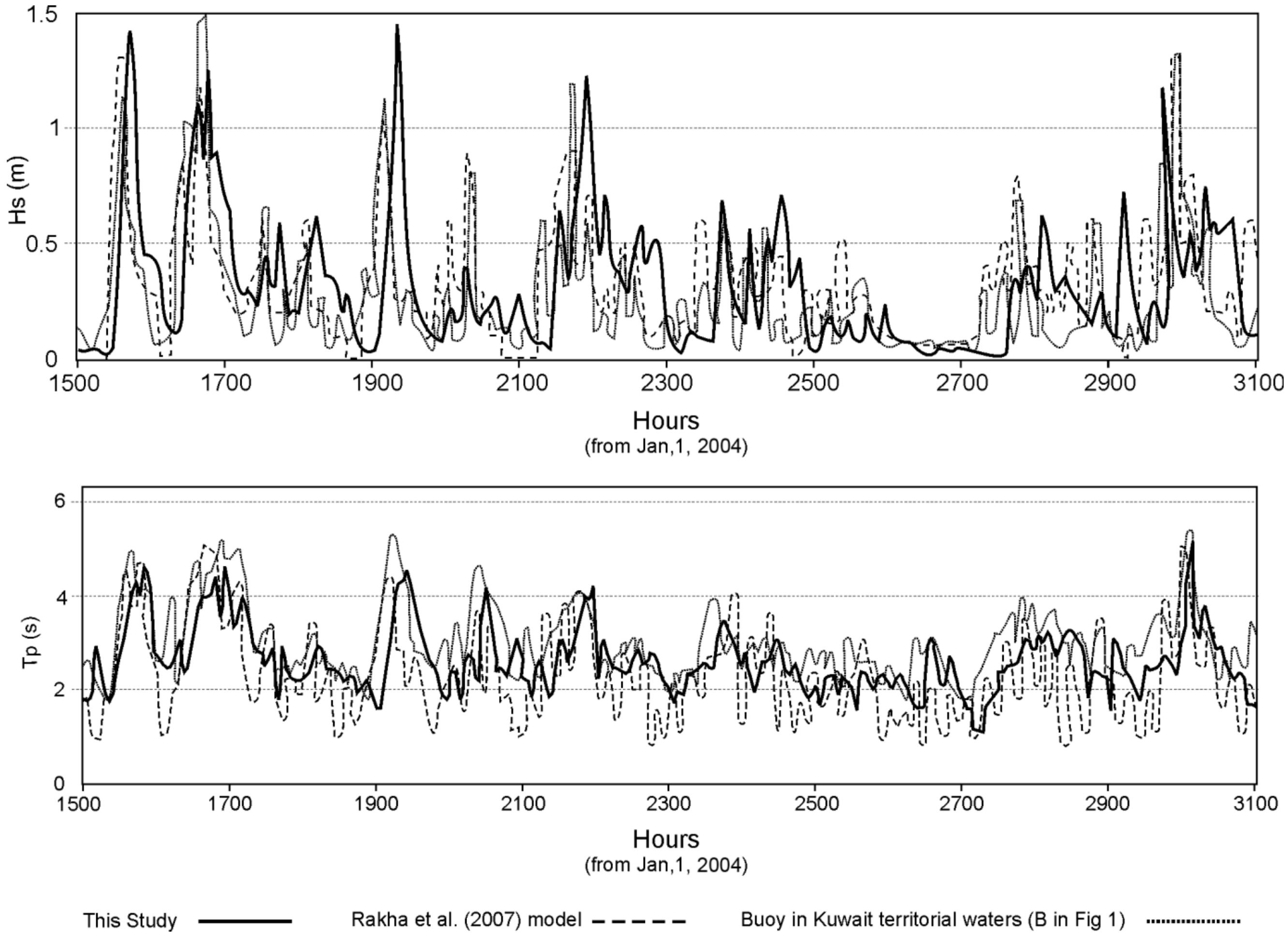


Figure 7. Comparison of the result of this study with Rakha et al. (2007) model and with a buoy in the Kuwait territorial waters (B in Figure 1).

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