NUMERICAL SIMULATION OF TROPICAL CYCLONES AND STORM SURGES IN THE ARABIAN SEA

Mohsen Soltanpour[1], Zahra Ranji[2], Tomoyo Shibayama[3], Sarmad Ghader[4], Shinsaku Nishizaki[5]

Winds, waves and storm surges of Gonu and Ashobaa, as two recent cyclones in the Arabian Sea and Gulf of Oman, are simulated by a system of WRF-FVCOM-SWAN. The employed models are separately calibrated using the available data. Surges are found to be highly dependent on coastal geometry and landfall location, rather than the storm intensity. Comparisons at different stations reveal that the results of models are in a good agreement with measured parameters. Negative surges are also observed in the enclosed basins of the Persian Gulf and Red Sea. The calibrated atmosphere-wave-ocean model can be utilized for the prediction of extreme events, expected to increase in future due to the impact of the climate change.

Keywords: Gulf of Oman; Arabian Sea; Tropical cyclones; Storm surge

INTRODUCTION

Storm surge is rising of the sea level over coastal regions due to the superposed actions of low pressure and the wind-induced surface shear stress. As the increase of temporary water level occurs at the same time of high wave action, it can result in disastrous flooding and coastal damages. Storm surges are more destructive if they coincide with high tides. However, the prevailing damage of cyclones at coasts are mainly located near the landfall, as the high winds/large waves are concentrated in the vicinity of the storm track. Rego and Li (2010b) demonstrated that the coastal surge of a hurricane depends to a large extent on the track of the storm.

Numerical modeling has been widely used to study the storm surge in recent years (e.g.; Shen et al., 2006; Weisberg and Zheng, 2006; Rego and Li, 2010b). Literature shows a large number of research studies on the impacts of storms on coastal areas (e.g.; Rego and Li, 2010a; Roelvink et al., 2009) and the effect of climate change on the cyclones (e.g., Woth, 2005; Woth et al., 2006; Sterl et al., 2009; Mel et al., 2013) in the last two decades. The global Sea Level Rise (SLR), resulted due to the climate change, has also increased the future danger of the storm surges. Lin et al. (2012) found that a 1-m SLR may cause the current New York City 100-year surge flooding to occur every 3-20 years and the 500-year flooding to occur every 25-240 years by the end of the century. Storm surge is also affected by the nonlinear interaction of surge and tide. Rego and Li (2010a) showed that the nonlinearity is important between the landfall position and locations within 2.5 × radius of maximum winds.

A large number of governing factors influence the storm surge. These include the geometry of coastline, topography and hydrography of the area, the wind field caused by the storm, severity and size of precipitation, etc. Thus, in order to obtain reliable surge results, accurate numerical modeling highly depends on the quality of input parameters and, in particular, existing of a fine bathymetry and accurate coastline geometry significantly improves the prediction of the storm surge. Colle et al. (2010) showed that a complex coastal geometry as well as shallow continental shelf enhance the rise of water level and storm surge.

Rezapour and Baldock (2014) noted that rainfall, as an important and frequently dominant hazard in terms of damage and death toll, has not been included in current hazard scales or indices. They presented a new rainfall subindex based on rainfall intensity, storm rainfall area, and the forward speed of the system to estimate the rainfall hazard. The atmosphere data, which is driving the surge model, robustly affects the simulations, in terms of spatial and temporal resolution as well as accuracy, and results in the peak values of storm surge (Wang et al., 2008). Howard et al. (2010) found a strong correspondence of surge simulations with global and regional climate models. They concluded that downscaling of the climate model could be alternatively replaced by a scaling factor found through the observation.

Arabian Sea and Bay of Bengal are two major basins of the tropical cyclones in the North Indian Ocean. Evaluation of historical cyclones in the Arabian Sea reveals that there might be a danger of more frequent intense cyclones in future. In particular, Cyclone Gonu, which occurred from June 1 to June 7, 2007, was the most intense tropical cyclone on record in the Arabian Sea. Literature shows a number of numerical studies of waves and storm surge of Gonu including Dibajnia et al. (2010) for utilizing cyclone

[1] Mohsen Soltanpour, K. N. Toosi University of Technology, soltanpour@kntu.ac.ir
[2] Zahra Ranji, K. N. Toosi University of Technology, zranji@mail.kntu.ac.ir
[3] Tomoyo Shibayama, Waseda University, shibayama@waseda.jp
[4] Sarmad Ghader, University of Tehran, sghader@ut.ac.ir
[5] Shinsaku Nishizaki, Waseda University, shinsaku-nisshi@fuji.waseda.jp

parametric model, Ghader et al. (2016) for applying combined atmospheric and wave models, and Fritz et al. (2010) for using a surge model.

The present study offers the simulations of two recent cyclones of Gonu (2007) and Ashobaa (2015) and the consequent storm surges, as two examples of intense and weak cyclones entered the Gulf of Oman, respectively. The modeling results are compared with the existing data at neighboring countries.

FIELD MEASUREMENTS

Fig. 1 shows the installed instruments at neighboring coasts of Arabian Sea and Gulf of Oman including tide gauges, Acoustic Doppler Current Profilers (ADCPs) and synoptic stations during the passages of the cyclones Gonu and Ashobaa. The data at Iranian coastlines are mostly selected from field measurements of the series of “Monitoring and Modeling Studies”, started by the Iranian Ports and Maritime Organization (PMO) in 2005. The rest of data are extracted from UHSLC (2017) database.

Figure 1. Wind stations (circle), ADCPs (square), tide gauges (triangular) during cyclone Gonu (violet) and Ashobaa (red)

NUMERICAL MODELING

A system of WRF-FVCOM-SWAN (see Fig. 2) is employed for the simulation of winds, waves and surges of cyclones Gonu and Ashobaa. The Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) provides the pressure and wind fields for the circulation model of FVCOM (Finite Volume Community Ocean Model) by Chen et al. (2007) and wind field for the wave model of SWAN (Simulating Waves Nearshore) by Booij et al. (1999).

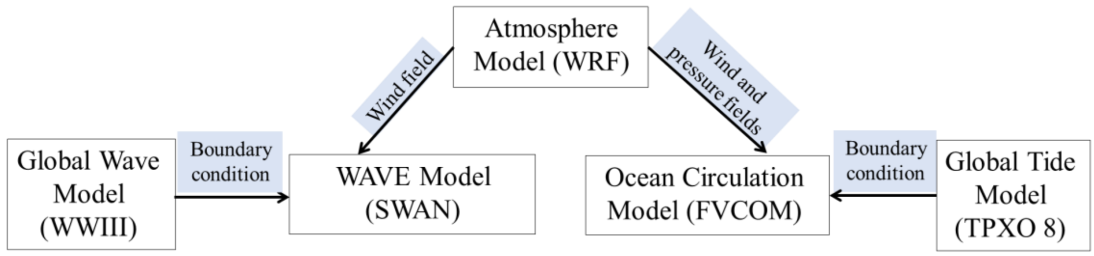

Figure 2. Modeling framework

The boundary conditions for wave and ocean models were adopted from the outputs of WAVEWATCH III (Enivronmental Modeling Center of National Weather Service, 2016) and tide model of TPXO 8 (Egbert and Erofeeva, 2002), respectively. These two global models have proved to provide accurate results in deep oceans. The surge is computed following the simple definition of Flather and Williams (2000), i.e. sea level elevation=predicted tide level + storm surge.

In order to include the effects of non-linear dynamic processes in shallow water, two separate simulations were run on identical grids, one with all the forcing terms and the other with only tidal forcing, as proposed by Wang et al. (2008). The surges were then determined by subtracting the outputs of the tide-only run from the results of modeling tide plus meteorological forcing. Sensitivity analysis and model calibration were conducted for all the employed models to ensure the performance of modeling system.

WRF model

WRF Model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting. ARW dynamical core was utilized here to reproduce Gonu and Ashobaa cyclones. Because of the high dependency of atmospheric models to initial conditions, computational grid, and the employed physics, a sensitivity analysis was conducted to find the best model configuration and physics for accurate simulation. Two nested grids, as presented in Fig. 3, demonstrated a good performance in simulation of the tracks of cyclones. Based on the test runs, the best model configurations and physics of Tables 1 and 2 were selected for each cyclone, respectively. Among the available physics, it was found that microphysics and cumulus schemes were more important in reproducing the cyclone intensity. Land surface scheme was also found to be effective on the simulation of cyclone track.

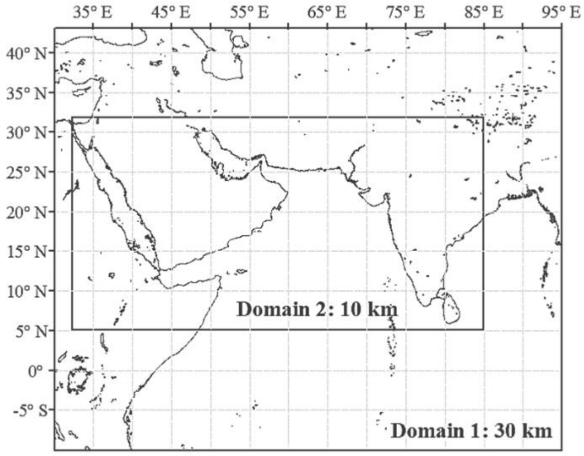

Figure 3. Domain of WRF model

Table 1. Configuration of WRF model

Tropical Cyclone	Ashobaa (2015)	Gonu (2007)
Model version	3.9.1	
Start time	June 6th-00 UTC	June 2nd-00 UTC
Initial and boundary condition	FNL (1°)	GFS ANL (0.5°)
Nesting type	Fixed nest	Fixed nest
Vertical resolution	40 terrain following sigma mass coordinate	
Horizontal resolution and domains	30 km: 62.5 E-17.5 N (210×180) 10 km: 58.31 E-19.03 N (517×277)	

Table 2. Physics of WRF model

Tropical Cyclone	Microphysics scheme	Cumulus scheme	Land surface scheme	Surface layer scheme	Radiation scheme	Planetary boundary layer scheme
Ashobaa (2015)	WSM3	Grell 3D Ensemble	Unified Noah Land Surface	MM5 Similarity	Dudhia & RRTM	YSU
Gonu (2007)	WSM6	Kain–Fritsch	5–layer Thermal Diffusion			

For evaluation of the reliability of atmospheric model, the results of modeling of two cyclone are compared with observations. Figs. 4, 5 and 6 respectively present the comparisons of the simulated tracks, intensities of cyclones at the cores and wind characteristics at synoptic stations with available data. An acceptable performance of WRF modeling is observed for both cyclones.

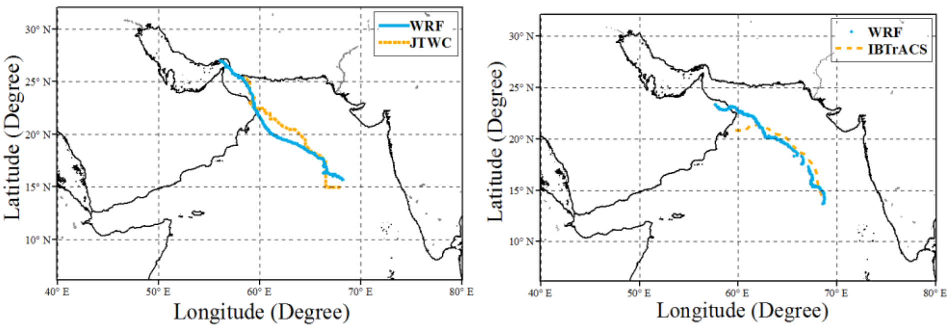

Figure 4. Comparisons of observed and simulated tracks of cyclones (left Gonu, right Ashobaa)

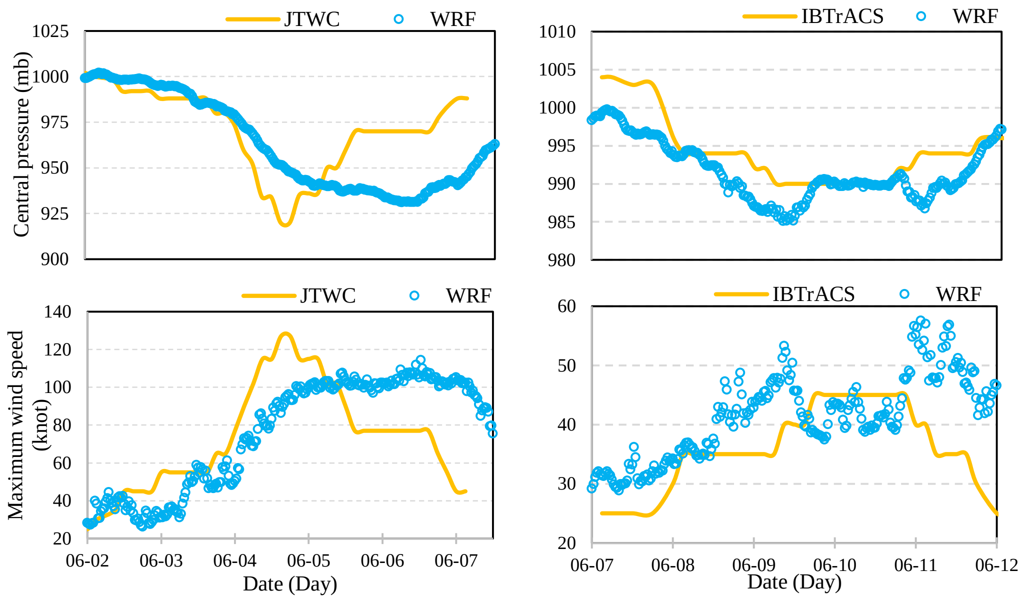

Figure 5. Comparisons of measured and simulated intensities of cyclones at the cores (left Gonu, right Ashobaa)

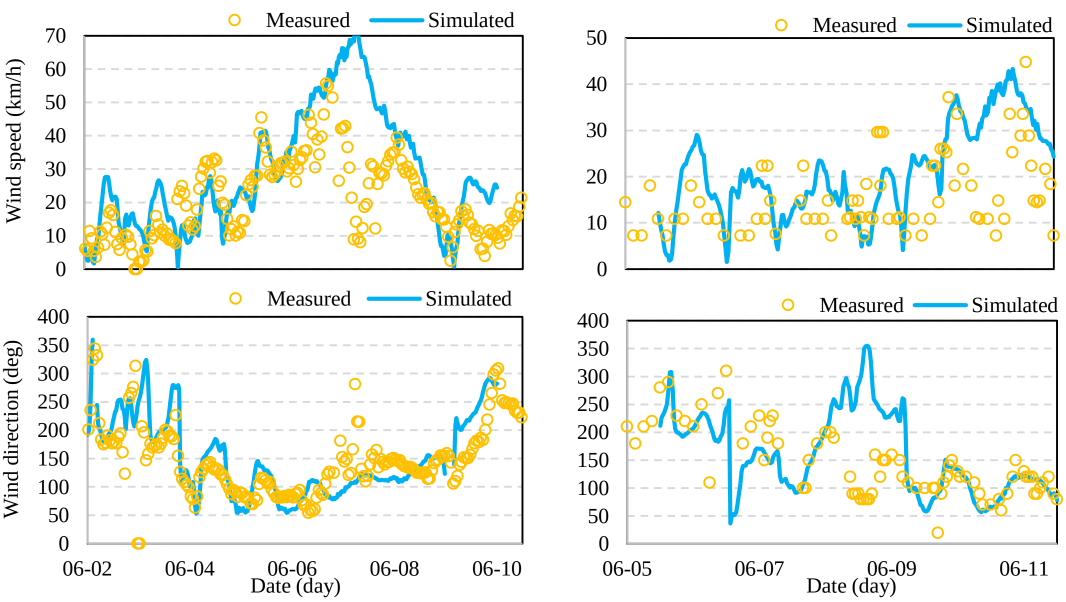

Figure 6. Comparisons of measured and simulated wind speed and wind direction at synoptic station SYN1 (left Gonu, right Ashobaa)

Wave and Ocean Models

Unstructured SWAN and FVCOM models are employed to simulate the waves and storm surges. An unstructured grid of 179203 elements with sizes ranging from 1100 (km^2) near the southern boundary, and 0.05 (km^2) at the vicinity of Chabahar Bay, is generated for both ocean and wave models (Fig. 7).

The coastline was extracted from global self-consistent, hierarchical, high-resolution geography database of GSHHG (Wessel and Smith, 1996). The employed bathymetry is the combination of 30-second gridded data of GEBCO (Sandwell et al., 2003) and nautical chart of Admiralty along the Iranian coastline, together with local hydrography measurements at some ports and coastal areas.

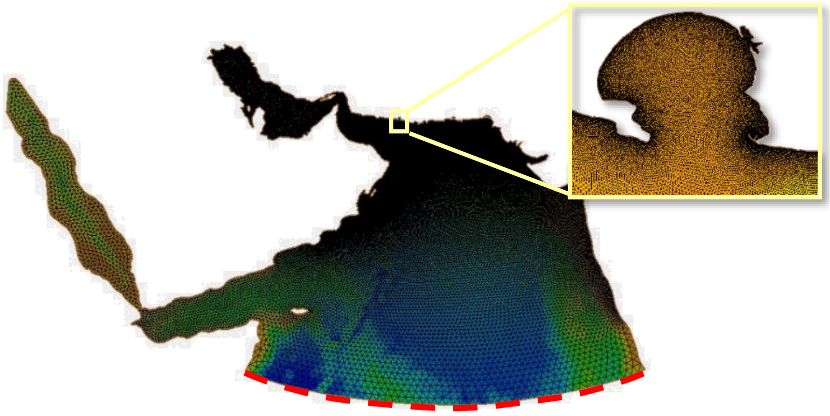

Figure 7. Computational grid of wave and ocean models

Table 3. Configuration and physics of wave model

Wave model	SWAN
Horizontal grid	1-50 km unstructured grid
Bathymetry	GEBCO 30 sec + local
Wind field	WRF
Wave-wave interaction	Triad and quadruplet
White capping	Alves & Banner
Wave growth	WESTH
Wave breaking	0.73
Bed friction	Madsen
Frequency resolution	40
Directional resolution	72
Boundary condition	WWIII

Table 4. Configuration and physics of FVCOM model

Horizontal grid	1-50 km unstructured grid
Vertical grid	10 sigma layers
Time step	2 sec
Bathymetry	GEBCO 30 sec + local
Open boundary	TPXO 8
Wind field	WRF
Pressure field	WRF
Vertical turbulence	M.Y 2.5 Closure model
Horizontal turbulence	Smagorinsky
Bed roughness	z0 = 0.005
Boundary condition	TPXO 8

Tables 3 and 4 present the applied model discretization in frequency, temporal/spatial domains and employed physics, which lead to maximum agreements between the simulations and measurements in wave and ocean models, respectively.

Fig. 8 shows the favorable agreements between the results of the unstructured SWAN model and measured wave data, i.e. significant wave height, peak wave period and mean wave direction. Model runs demonstrated that proper definition of wave characteristics at the open boundary plays an important role in the simulation of peak periods where bi-modal waves of wind seas and swell exist.

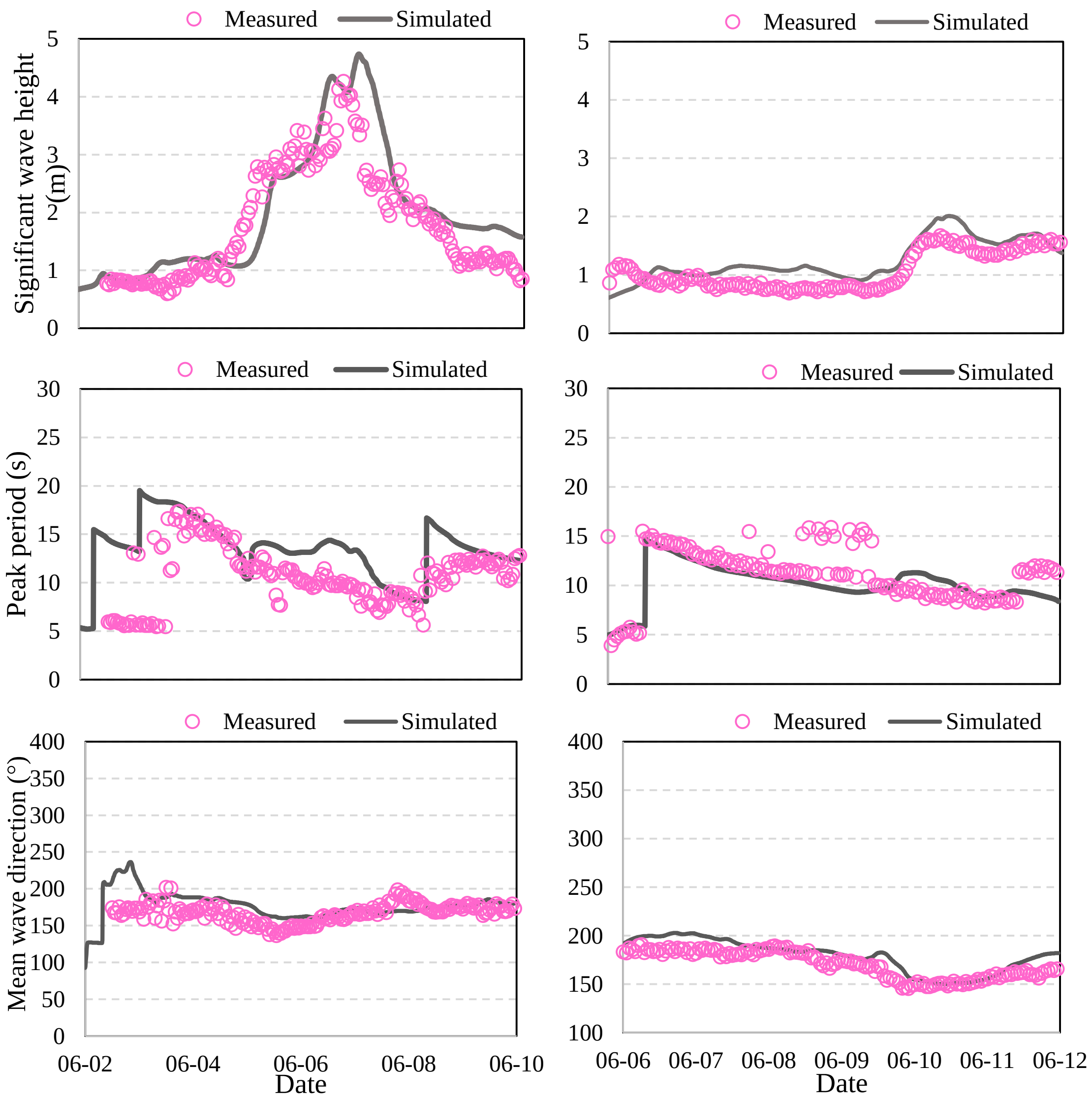

Figure 8. Comparisons of the simulated and measured wave parameters for Gonu at AW2 (left) and Ashobaa at Rodik (right)

Figs. 9 and 10 present the comparisons between the simulated surges of Gonu and Ashobaa with measurements at different stations around the Arabian Sea. Modeling accuracy of the surge of cyclone Gonu looks acceptable but the peak surges of cyclone Ashobaa is somehow underestimated. It should be noted that accurate basin shape, fine bathymetry and proper grid size are essential for a good modeling of storm surge. The lack of these input parameters at present modeling has led to a considerable underestimation of predicted surge at Karachi. This can be considerably improved if a high resolution bathymetry is given to the numerical model. Filtering the tide fluctuation out of the measured water level is also a source of error in some stations, e.g. Rodik where filtering is not precise due to lack of measured long-term water level resulting in a limited number of reliable tidal constituents.

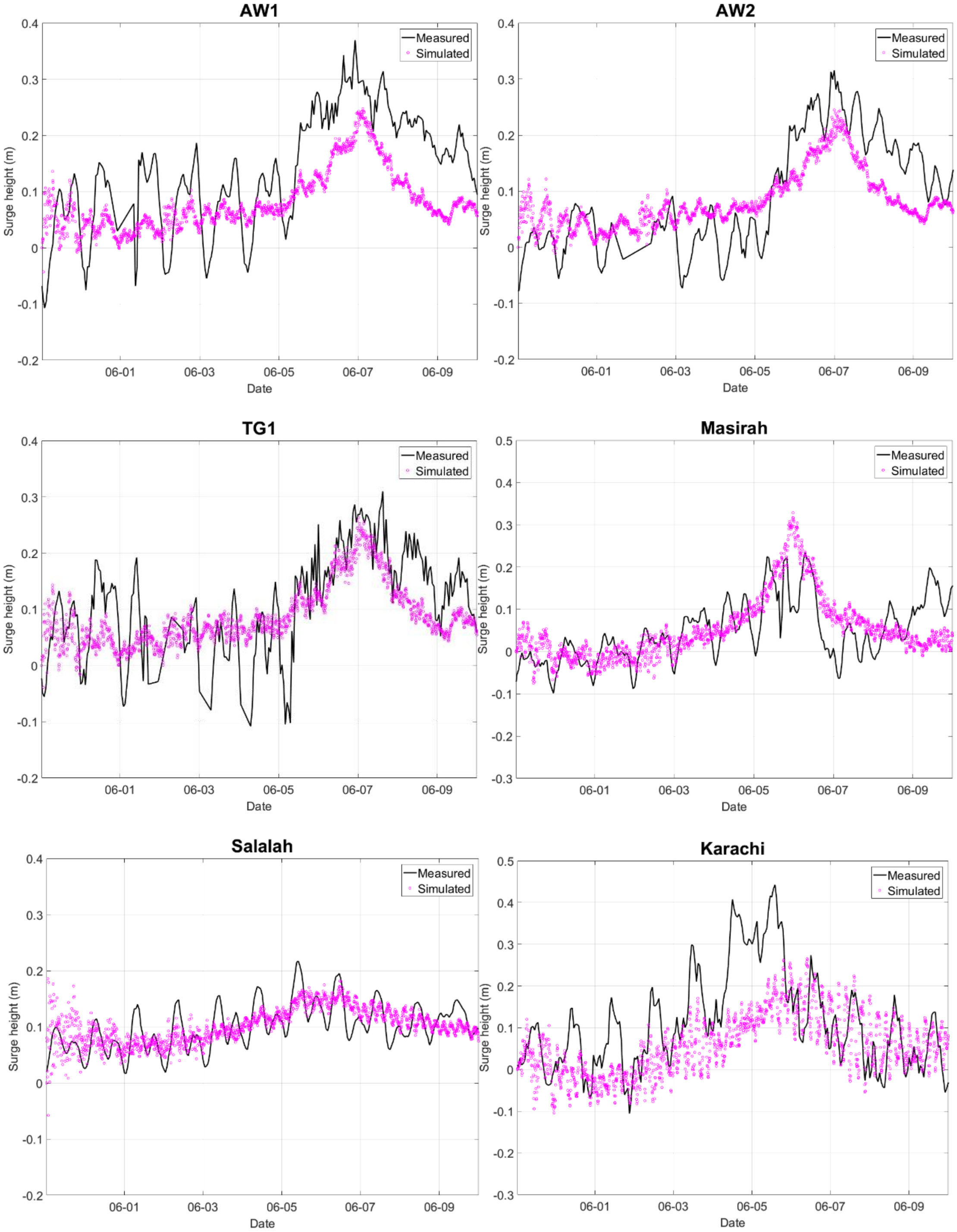

Figure 9. Storm surges of cyclone Gonu at different stations

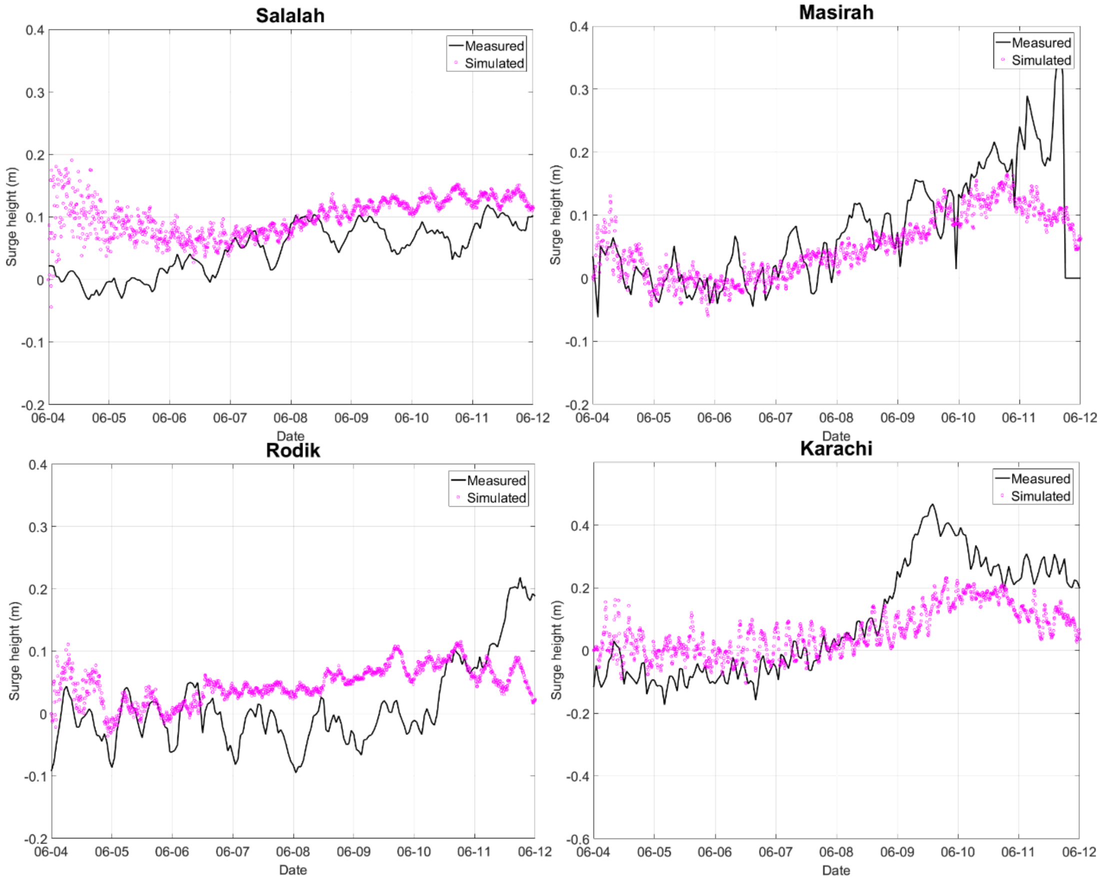

Figure 10. Storm surges of cyclone Ashobaa at different stations

Fig. 11 and 12 provide the distributions of maximum and minimum surges of cyclones Gonu and Ashobaa over the Arabian Sea, respectively. Maximum surge values of cyclone Gonu is in the vicinity of the track, while greater surges are observed in the bays along Indian coastlines as well as the Persian Gulf for the weak Ashobaa cyclone. This might be related to the low forward speed of Ashobaa that provides enough time for the long waves travelling to far distances.

Similar patterns of the maximum negative surges of two cyclones are observed at the northwest part of the Persian Gulf. However, Red Sea experiences a greater negative surge for the more intense Gonu. The negative surge in the Persian Gulf also looks independent of the negative surges of both cyclones. Moreover, both positive and negative surges can be distinguished in the Persian Gulf at the same time (Fig. 13). As the cyclone is still very far from the enclosed basin, another wind system, so-called Shamal wind from NW to SE, is responsible for these positive and negative surges at two corners of the Persian Gulf. Shamal wind results in negative surges at northwestern parts of the Persian Gulf as they displace water from NW corner to SW part of the gulf.

Fig. 14 shows an example of the positive and negative surges at Bahrain station in the Persian Gulf, after the storm attack (see Fig. 1). The time difference of the positive and negative surges, originated by the cyclone, are about 3 days. The observed surge at this station is higher than the surge at the vicinity of the far landfall location, i.e. Masirah station in Fig. 1, which highlights the effect of partially enclosed basin.

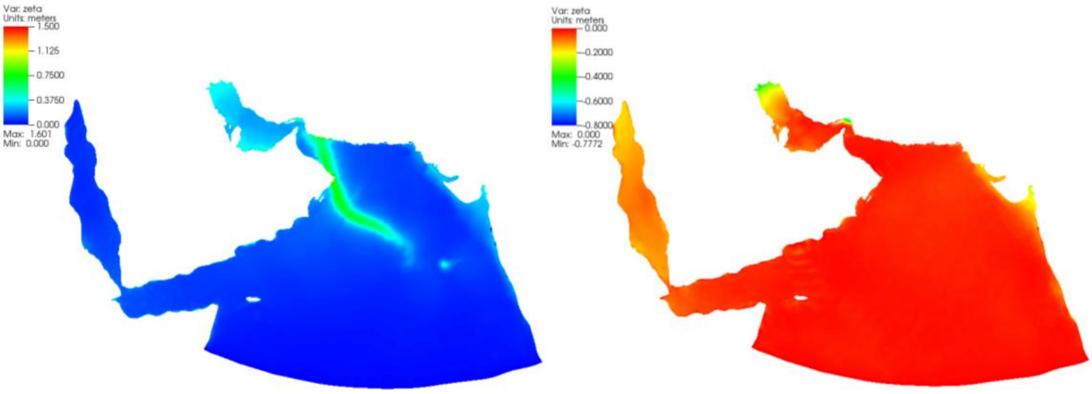

Figure 11. Maximum positive surge (left) and minimum negative surge (right) over the Arabian Sea for the cyclone Gonu

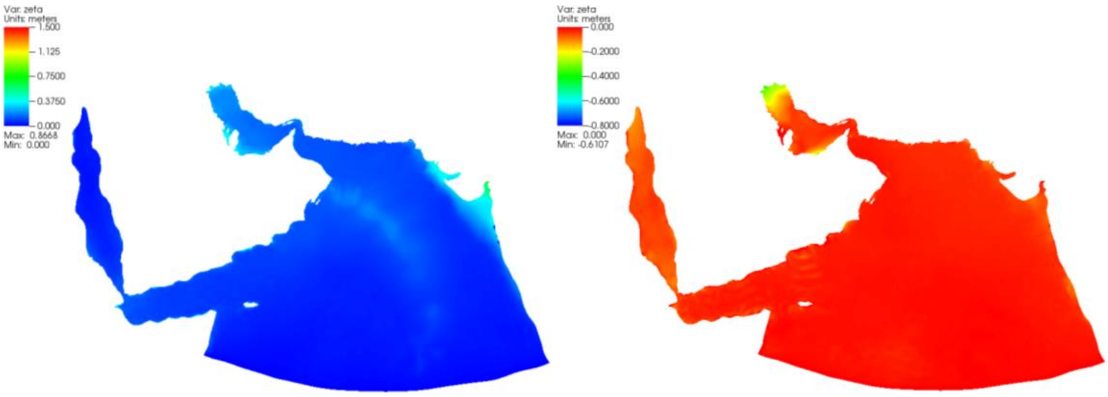

Figure 12. Maximum positive surge (left) and minimum negative surge (right) over the Arabian Sea for the cyclone Ashobaa

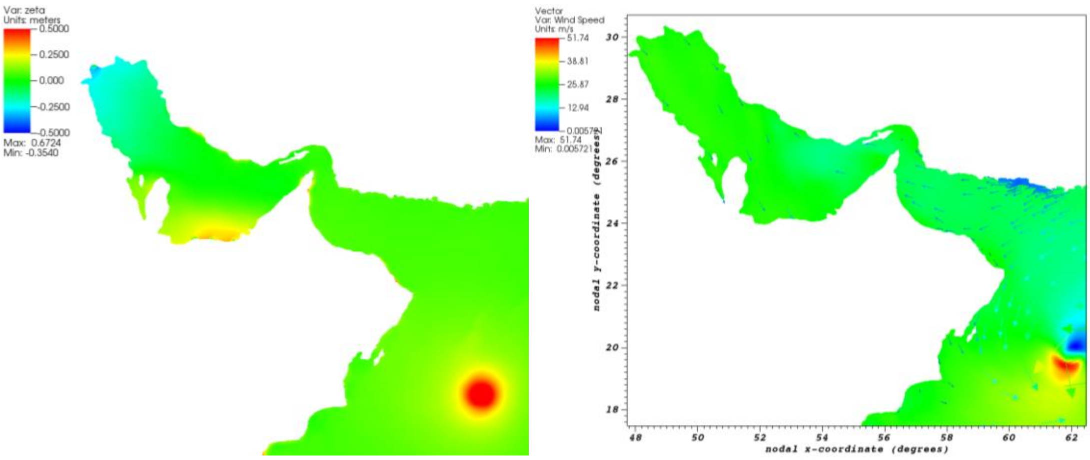

Figure 13. Negative and positive surges inside the Persian Gulf (left), wind speed vector (right) at Jun 5, 4 am.

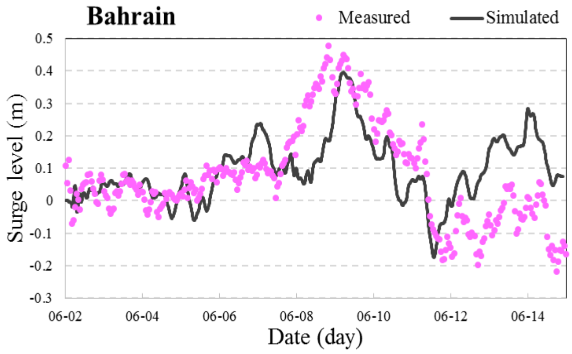

Figure 14. Negative and positive surges of cyclone Gonu at Bahrain station in the Persian Gulf

SUMMARY AND CONCLUSION

Cyclone Gonu (2007), the most intense tropical cyclone on record in the Arabian Sea, and cyclone Ashobaa (2015), a recent cyclone that affected Iranian coastline in the Gulf of Oman, were simulated as two samples of strong and weak cyclones in the region. A system of calibrated WRF-FVCOM-SWAN was employed for the simulations of winds, waves and surges of the cyclones.

It was observed that when the cyclone Gonu traveled across the Arabian Sea, the local winds in far enclosed basins of the Persian Gulf and the Red Sea could generate significant negative surges due to the limited exchange of water with open sea. The modeling results, in general, agrees with observed surge data in the Persian Gulf, Gulf of Oman and Arabian Sea. However, less discrepancies between the outputs of atmospheric and ocean models with measurements can be achieved if high quality bathymetries and coastlines are employed. The presented model can be utilized to assess the future probable impact of climate change on the intensity of cyclones and storm surges in the region.

ACKNOWLEDGEMENT

The authors would like to thank the Directorate General for Coastal and Port Engineering of Port and Maritime Organization (PMO) of Iran for providing the data of monitoring projects along the Iranian coastline.

REFERENCES

Booij, N., R. C. Ris, and L. H. Holthuijsen. 1999. A third-generation wave model for coastal regions: 1. Model description and validation, *Journal of Geophysical Research: Oceans,* 104, 7649-7666.

Chen, C., H. Huang, R. C. Beardsley, H. Liu, Q. Xu, and G. Cowles. 2007. A finite volume numerical approach for coastal ocean circulation studies: Comparisons with finite difference models, *Journal of Geophysical Research,* 112, C03018.

Colle, B. A., K. Rojowsky, and F. Buonaito. 2010. New york city storm surges: Climatology and an analysis of the wind and cyclone evolution, *Journal of Applied Meteorology and Climatology,* 49, 85-100.

Dibajnia, M., M. Soltanpour, R. Nairn, and M. Allahyar. 2010. Cyclone gonu: The most intense tropical cyclone on record in the arabian sea," in *Indian ocean tropical cyclones and climate change*. vol. 149-157, Y. Charabi, Ed., ed The Netherlands: Springer.

Egbert, G. D. and S. Y. Erofeeva. 2002. Efficient inverse modeling of barotropic ocean tides, *Journal of Atmospheric and Oceanic Technology,* 19, 183-204.

Enivronmental Modeling Center of National Weather Service. 2016. WAVEWATCH III MODEL DATA ACCESS. Available: http://polar.ncep.noaa.gov/waves/ensemble/download.shtml.

Flather, R. A. and J. A. Williams. 2000. Climate change efffects on the storm surge: Methodologies and results, in *Climate scenarios for water-related and coastal impact*, J. Beersma, M. Agnew, D. Viner, and M. Hulme, Eds., ed Norwich, 66–78.

Fritz, H. M., C. D. Blount, F. B. Albusaidi, and A. H. M. Al-Harthy. 2010. Cyclone gonu storm surge in oman, *Estuarine, Coastal and Shelf Science,* 86, 102-106.

Ghader, S., D. Yazgi, S. A. Haghshenas, A. Razavi Arab, M. Jedari Attari, A. Bakhtiari, *et al.* 2016. Hindcasting tropical storm events in the oman sea, *14th International Coastal Symposium*, Journal of Coastal Research, 1087 – 1091.

Howard, T., J. Lowe, and K. Horsburgh. 2010. Interpreting century-scale changes in southern north sea storm surge climate derived from coupled model simulations, *Journal of Climate,* 23, 6234-6247.

Lin, N., K. Emanuel, M. Oppenheimer, and E. Vanmarcke. 2012. Physically based assessment of hurricane surge threat under climate change, *Nature Climate Change,* 2.6, 462–467.

Mel, R., A. Sterl, and P. Lionello. 2013. High resolution climate projection of storm surge at the venetian coast, *Natural Hazards and Earth System Sciences*, 13, 1135–1142.

Rego, J. L. and C. Li. 2010a. Nonlinear terms in storm surge predictions: Effect of tide and shelf geometry with case study from hurricane rita, *Journal of Geophysical Research,* 115, C06020.

Rego, J. L. and C. Li. 2010b. Storm surge propagation in galveston bay during hurricane ike, *Journal of Marine Systems*, 82 265–279.

Rezapour, M. and T. E. Baldock. 2014. Classification of hurricane hazards: The importance of rainfall, *Weather and Forecasting,* 29, 1319-1331.

Roelvink, D., A. Reniers, A. van Dongeren, J. van Thiel de Vries, R. McCall, and J. Lescinski. 2009. Modelling storm impacts on beaches, dunes and barrier islands, *Coastal Engineering,* 56 1133–1152.

Sandwell, D. T., S. T. Gille, and W. H. F. Smith. 2003. *Bathymetry from space: Oceanography, geophysics and climate,* Bethesda, Maryland, 24 pp.

Shen, J., W. Gong, and H. V. Wang. 2006. Water level response to 1999 hurricane floyd in the chesapeake bay, *Continental Shelf Research,* 26, 2484–2502.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda*, et al.* 2008. *A description of the advanced research wrf version 3*, 113 pp.

Sterl, A., H. van den Brink, H. de Vries, R. Haarsma, and E. van Meijgaard. 2009. An ensemble study of extreme storm surge related water levels in the north sea in a changing climate, *Ocean Science,* 5, 369–378.

University of Hawaii Sea Level Center. 2017. School of Ocean and Earth Science and Technology. Available: https://uhslc.soest.hawaii.edu.

Wang, S., R. McGrath, J. Hanafin, P. Lynch, T. Semmler, and P. Nolan. 2008. The impact of climate change on storm surges over irish waters, *Ocean Modelling,* 25 83–94.

Weisberg, R. H. and L. Zheng. 2006. Circulation of tampa bay driven by buoyancy, tides, and winds, as simulated using a finite volume coastal ocean model, *Journal of Geophysical Research,* 111, C01005.

Wessel, P. and W. H. F. Smith. 1996. A global, self-consistent, hierarchical, high-resolution shoreline database, *Journal of Geophysical Research,* 101, 8741-8743.

Woth, K. 2005. North sea storm surge statistics based on projections in a warmer climate: How important are the driving gcm and the chosen emission scenario?, *Journal of Geophysical Research*, 32, L22708.

Woth, K., R. Weisse, and H. von Storch. 2006. Climate change and north sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models, *Ocean Dynamics,* 56, 3–15.