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Beraud, C.P.C; Kelly, D.M.

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C.P.C Beraud[1], D.M. Kelly[2] / DKAF Coastal[2]
[1] claire.beraud@cefas.co.uk, [2] dkafcoastal@gmail.com
[1] Centre for Fisheries and Aquaculture Science, Pakefield Road, Lowestoft, NR33 OHT, UK
[2] Beccles, NR34 9UD, Suffolk, UK

Abstract – **Tropical Cyclone (Hurricanes and Typhoons) intensity has increased in recent years, in response to warming sea temperatures. There is therefore the need to predict the cyclone-induced inundation and is paramount to protect local population and limit the cyclone-related risk. The category-5 cyclone Gonu is the strongest observed cyclone in the Arabian Sea and hit Oman in June 2007, causing 49 deaths. The JTWC Automated Tropical Cyclone Forecasting database provides simulated winds speeds and atmospheric pressure and has been validated against observations such as satellite where available. In order to predict the water inundation levels due to the tropical storms the path and strength of the cyclone need to be included in a marine model that simulates waves and sea level response.**

We have developed a methodology to incorporate spatially and temporally varying winds and pressure into a coupled TELEMAC2D-TOMAWAC system. This model has been applied to simulate the Gonu tropical cyclone event with calibration of the simulated waves by comparing with observations.

Furthermore, results are presented of "what if" scenarios, whereby the track of Gonu-like events is shifted further south to assess the potential impact of a similar event on other parts of Oman.

Different model configurations enable the breaking-down of the different cyclone components: the effect of local depression and wind are presented. Uncertainties on the simulation of wind- and wave-induced flooding are discussed and will be further developed in future work with the Omani meteorological institute providing additional observation data that would help us in the calibrating and validating process of the model.

Keywords: Oman, cyclone simulation, tropical cyclone Gonu, coupled TELEMAC2d-TOMAWAC

I. Introduction

Tropical cyclones are extremely powerful and harmful natural events. One such event was Gonu, a category 5 (maximal) tropical cyclone, which sits among the top 10 costliest known North Indian Ocean cyclones; according to the Oman News Agency Gonu took 49 lives in the country and costed around $4.2 billion (2007 USD) in Oman. Gonu (see Figure 1, bottom) developed in the eastern Arabian Sea from the 1st of June 2007 and made landfall at the most easterly tip of Oman near Ras al-Hadd. It then moved in a northward direction into the Gulf of Oman and made a second landfall in Iran that dissipated its energy. Gonu characteristics were an eye diameter reaching 40 miles (64km), a wind maximum velocity up to 145 miles per hour (65 m/s) and heavy precipitations up to 934 mm at Aljabl alasfer near Muscat (Figure 1). Gonu travelled around 10 degrees in both latitude and longitude throughout the Arabian Sea and impacted the following countries: Oman, Iran, United Arab Emirates and Pakistan.

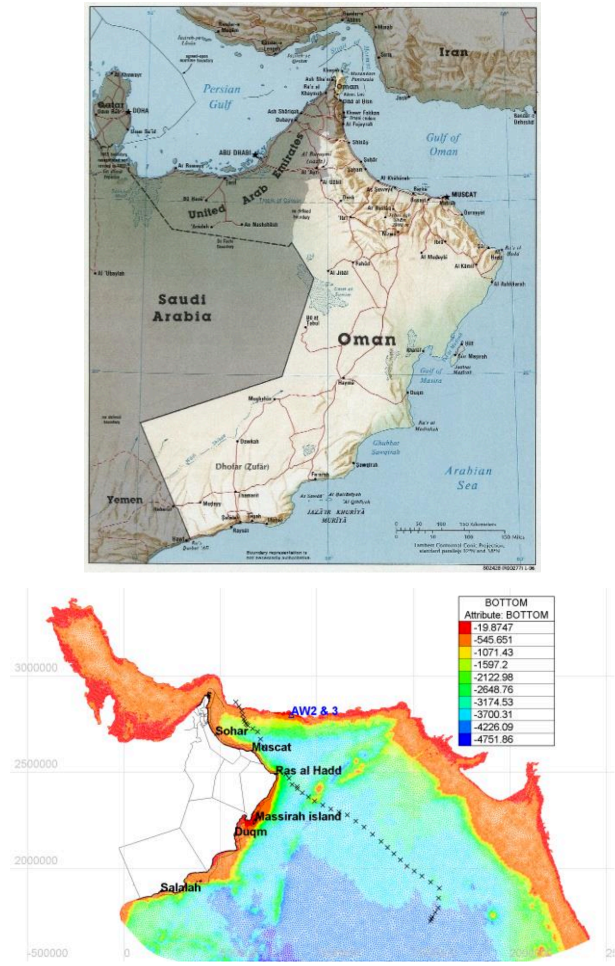

Figure 1. bottom: model bathymetric mesh with Gonu track downloaded from JTWC indicated with crosses, the principal cities/villages and islands are noted. The AWAC (Acoustic Doppler Wave & Current Profiler) stations AW2 and AW3 are in Iran and indicated in blue; x- and y- axis are in metre projection UTM40N. top: overview of Oman topography (CIA 1996 map) with coordinates in latitude-longitude.

Along the Gulf of Oman, several tide gauges failed and could not record any observation of Gonu passing. In order to have further information on this event over Oman [1] established a protocol to collect high water marks and present them in [2] together with the development of an ADCIRC flood model. High water marks can be elevations of water marks on trees, buildings or debris found and results from the addition of the following two hurricane-induced inundation components: storm surge and storm waves. Reference [3] also reported a high-water mark of 5m at Ras al-Hadd. Gonu maximum observed wind has been reported in Oman: wind at Ras al-Hadd was 46 m/s on the 05/06/2007 in the evening and was 20 m/s near Muscat on the 06/06/2007 13:00:00.

Time-series of wind and wave information during the cyclone Gonu event have been measured at the stations AW2 and 3 (Figure 1, bottom) within and in the vicinity of Chahbahar bay, Iran; further information on the deployed stations can be found in [4] and [5] and observation time-series have been discussed in [5] and [6]. Time-series data at AW3 have been extracted from [10].

In Oman, mountains are present in the northern and southern part of the country (Figure 1, top), and 80% of the population lives in low-lying areas [7] where development of refinery, fish and shrimp farms, desalination plants and real estate development is planned. Aware of the damage that can induce an event such as a Gonu-like cyclone, the Omani government wants to better understand the inundation dynamics and investigate potential cyclone impact if landing hit one of those areas in development.

II. Model setup

A. *Site location and model domain*

The numerical mesh covers the Oman and Persian gulfs. Cell size ranges from 40m to 12km and totalled ~200,000 cells in number. The refined areas are located on the eastern side of Oman (Figure 1, bottom). The bathymetry stems from GEBCO (General Bathymetric Chart of the Oceans), ETOPO1 (1 arc-minute topography, open source) and local EOMAP (commercial) data sources, which all have been standardized by analysing LAT predictions.

Development to update the Maximum Envelope Of Water every time-step and amend the drag coefficient depending on the wind strength has been done in TELEMAC-suite version v8p1; as the latest version did not allow the use of different meshed in TELEMAC and TOMAWAC, the same mesh was employed to run the coupled TELEMAC-2D and TOMAWAC models. TELEMAC-2D reproduced the surge induced by the depression (inverse barometer) and the wind stresses, TOMAWAC predicted the generation of waves due to the winds. Almost the full history of Gonu was simulated (i.e. from 2nd to 8th June 2006, with cyclone beyond the TELEMAC domain on the 1st June). TELEMAC and TOMAWAC run with a time-step of 10 and 450 seconds, respectively, making TOMAWAC be coupled at every 45th to TELEMAC to limit the running time.

B. *Creation and use of wind and pressure parametric forcing files*

This work builds on developments by D. Kelly at the National Hurricane Centre (NHC) in Miami. An automatic tool has been developed that generates cyclone wind and pressure fields using the following cyclone information: the cyclone track positions (in latitude and longitude) and its intensity defined with both the maximum wind speed (and radius if available) and the storm central pressure. Such information can be downloaded from the Joint Typhoon Warning Center (JTWC, https://www.metoc.navy.mil/jtwc/jtwc.html?best-tracks) for most of the past cyclones and [8] provides a description of the cyclone data compilation and formatting. It is important to note that those tracks are the best available for now, however some data may be improved [10]. It is hoped that track data may be completed or may vary in the future. The tool uses formulations from wind model of Holland ([9]); this stand-alone binary tool can be run in either Linux or Windows and creates a Selafin forcing file.

For this work the tool has been run using JTWC-downloaded information on the super cyclonic storm Gonu and data have been refined in time using linear interpolation. The created atmospheric forcing file is read by the TELEMAC and the TOMAWAC models through the keyword BINARY ATMOSPHERIC DATA FILES. The fortran subroutine PROSOU.f has been amended and is called in the models steering files to adequately include the wind and pressure parametric fields.

III. Model calibration and validation

Calibration process consisted in checking the wind fields generated from the JTWC-downloaded information. Once we were satisfied with the physics of the atmospheric forcing, wave generation has also been calibrated to reproduce wave time-series as measured at AW2, Chahbahar bay, Iran. The validation process was carried out by comparing the reported and simulated inundation lands and water levels. This modelled inundation will only be induced by wind stresses, pressure depression, and wave radiation forces. The lack of precipitation forcing, and of wave run-up process is discussed in the next sections.

A. *Calibration*

Just before Gonu landing, observations reported a wind strength of 20m/s at Muscat and 46 m/s at Ras al-Hadd. For those two locations, wind magnitude simulated differs by 7.5 and 22%, respectively (Table I). This mismatch may be due to the linear interpolation of data in the Gonu track and it is also probable that the landing induced some changes in wind dynamics that are not included in the [9]'s model.

To generate waves, the TOMAWAC parameters have been calibrated; the following parameters gave the best predictions: The wind generation followed Janssen's model (WAM cycle 4) associated with a standard value of wind generation coefficient (1.2) have been used. A linear wave growth has been chosen. Wind drag coefficient has been calculated using the Garratt (1977) [13] linear form, a formulation recommended for hurricane wind and used in the NHC Sea, Lake, and Overland Surges from Hurricane (SLOSH) model and the ADvanced CIRCulation (ADCIRC) model.

Table I : Wind strength in m/s measured and TELEMAC predictions during the Gonu event

Date	**06/06/2007 13:00:00**	**05/06/2007 evening**
Location	Near Muscat	at Ras al-Hadd
Model	18.5	36.0
Obs.	20 m/s	46 m/s
Relative error	7.5%	22%

Wave energy was dissipated by white-capping, bottom friction and depth-induced breaking. As waves propagate both in very deep water over the Gulf and in shallow water in coastal areas, non-linear transfer between frequencies (quadruplet interactions) was activated together with the triad interactions. A wave growth limiter was used to limit numerical instabilities; waves were not generated in water shallower than 0.4m. In Figure 2 the wave model reproduces the dynamics in wave growth but under-estimates the final wave height. This lack of wave energy (smaller wave height) agrees with the wind under-prediction.

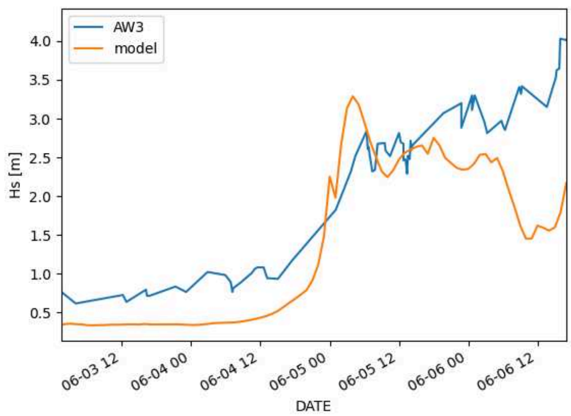

Figure 2. Evolution of wave height measured at station AW3 (extracted from [10]) and modelled during the Gonu event at the station AW3 location (see Figure 1)

B. Validation

The high-water mark (the elevation of the water level above the Mean Sea Level) was measured at Ras-al-Hadd on the 5th of June 2007 as 5 meters. In the model the wind and pressure-induced inundation levels are predicted to 0.8m in ebbing water topped up by 5 to 6 meters wave heights at the coast. The addition of the latter two components slightly exceeds the measured level.As reported in [1] land has been inundated during the Gonu cyclone event. The high-water marks reported in [2] have been plotted in Figure 3along with the prediction of maximum water levels and maximum wave heights from the model. We see that all inundated areas (at coloured diamonds locations) have been predicted to be under water, although there is a mismatch between the predicted and reported inundation levels. Inundation seems more important closer to the eastern tip of Oman, where wave heights are predicted to be large (more than 5m) and close to the shoreline. Wave runup effect is missing in the model and may explain the difference in inundation levels there. In the vicinity of Muscat high amount of rain has been reported ([11]) that are not reproduced in the model and may explain the differences between reported and predicted water levels.

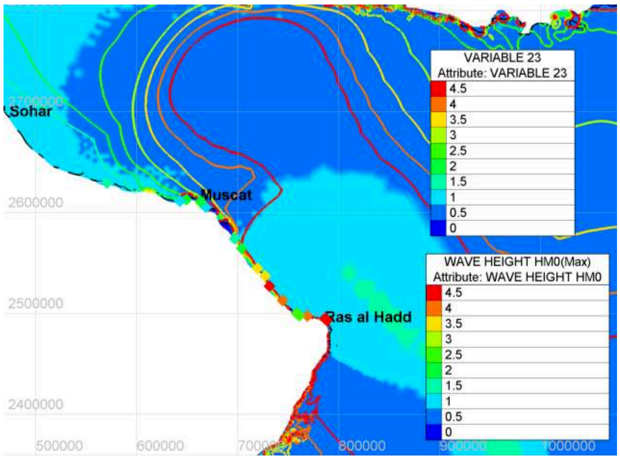

Figure 3. Modelled Maximum Elevation Of Water (m) predictions are indicated with the background colours, the maximum wave heights (m) are showed with the contour lines and the diamonds colour represents the reported high-water marks (m) from [2]

IV. Gonu simulation prediction details

A. *Inundation at Ras al-Hadd*

The observed inundation extent at Ras al-Hadd was well reproduced in the model thanks to a well refined mesh at the coastal tip. The strong cyclone wind was pushing the water toward the lowest land at Ras-al-Hadd (Figure 3).

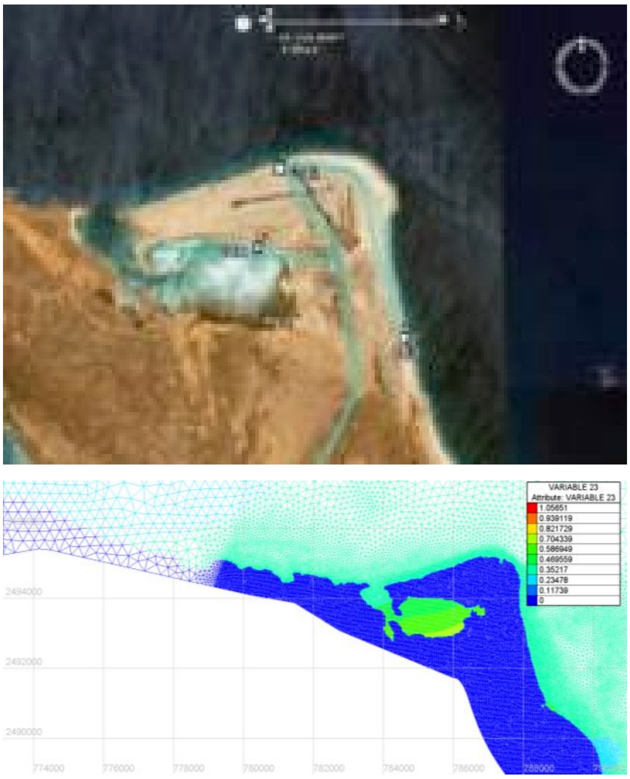

Figure 4. Inundated area near Ras al-Hadd (top, extracted from [2]) and simulated (bottom) MEOW at the end of the Gonu event

B. *Maximum predicted waves and water level*

The TOMAWAC simulated maximum wave height over the Gonu event agrees with the wave results from [10] using the WAVAD model (Figure 5). No calibration parameters are available within the WAVAD model and the wind model used was based on the parametric representation of [9].

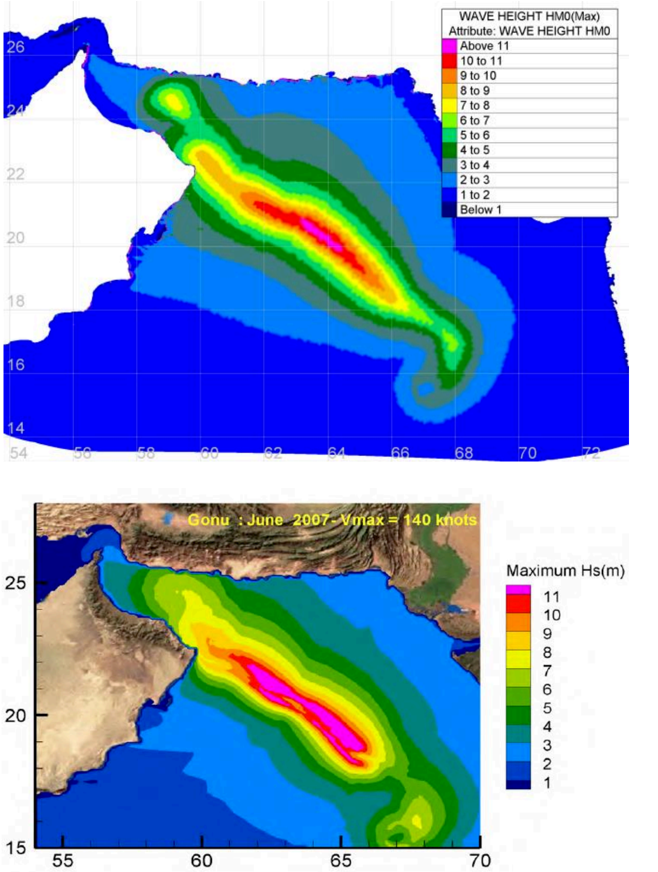

Figure 5. Max. Significant Wave height over duration of the cyclone. The scale runs from 1m (blue) to 11m (purple) for TOMAWAC predictions (top) and WMO-WAVAD predictions extracted from [10] (bottom)

V. Realistic storm-like-Gonu with a more southern landfall

In this simulation we discarded the tide as we wanted to focus on the cyclone effect and look at the different cyclone components to better understand the storm dynamics before and when the cyclone land-fell in a low-lying coast of Oman.

A. *Simulation of alternative trajectories*

The initial Gonu track position has been moved by four degrees southward and the new cyclone trajectory landfalls at the Massirah island. Although it is probable that such a cyclone moving over shallow waters will be impacted by the seabed, it is very difficult to determine how the cyclone trajectory and strength may change near and after this landfall and it has been decided to not amend the strength in cyclone characteristics (maximum velocity, diameter, and lowest pressure).

B. *Cyclone components*

Impact along the track can be clearly seen in Figure 6 with the Maximum Elevation Of Water (MEOW) along the track of the cyclone.

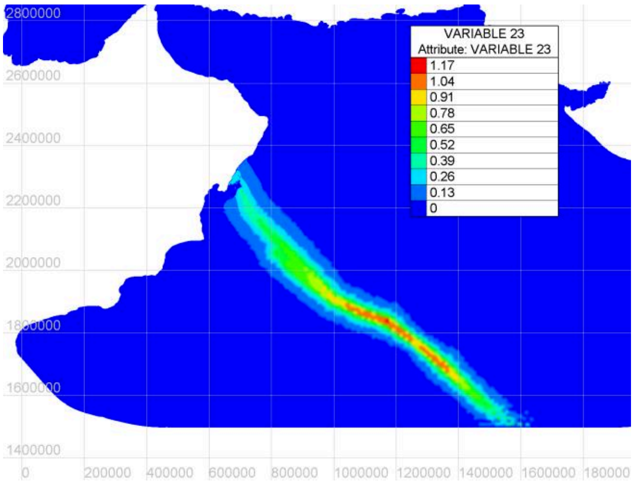

Figure 6. Predicted Maximum Elevation of Water (MEOW in m) over the simulation.

The wind and pressure effects on the maximum water elevation level can be seen in Figure 7. When the model is forced with the wind field only, the inundation happens next to the shoreline where the wind blows toward the south, and the water is pushed against the shore and piles up there; with both wind and pressure being forced, both coastal areas and along the storm track areas are subjected to a rise of water level, with the former being mainly driven by a wind-effect and the later by a pressure effect.

VI. RESULTS AND DISCUSSION

Although the model wind predictions reproduce the spinning dynamics of the wind field, some uncertainties in wind magnitude remain noticeably in vicinity of landfall. Underestimation in wind strength causes an underestimation in wave height predictions, although the overall maximum wave height is comparable to other validated model outputs. We hope that in the future the JTWC dataset will be improved with more accurate wind field when approaching the landfall.

The lack of wave run-up and rainfall can explain some mismatches between predicted and simulated levels of inundation. We assume the wave runup to be large when the cyclone is moving parallel and close to the northern Omani coast. It would be interesting to convert wave spectral predictions from TOMAWAC into wave time-series in water surface using the WAFO module in Python, similarly to what [12] did. The model is also missing the inundation triggered by extreme rainfall and flushing along valleys that has been reported [11], and further model development will focus on reproducing the inland and coastal inundation due to riverine flooding.

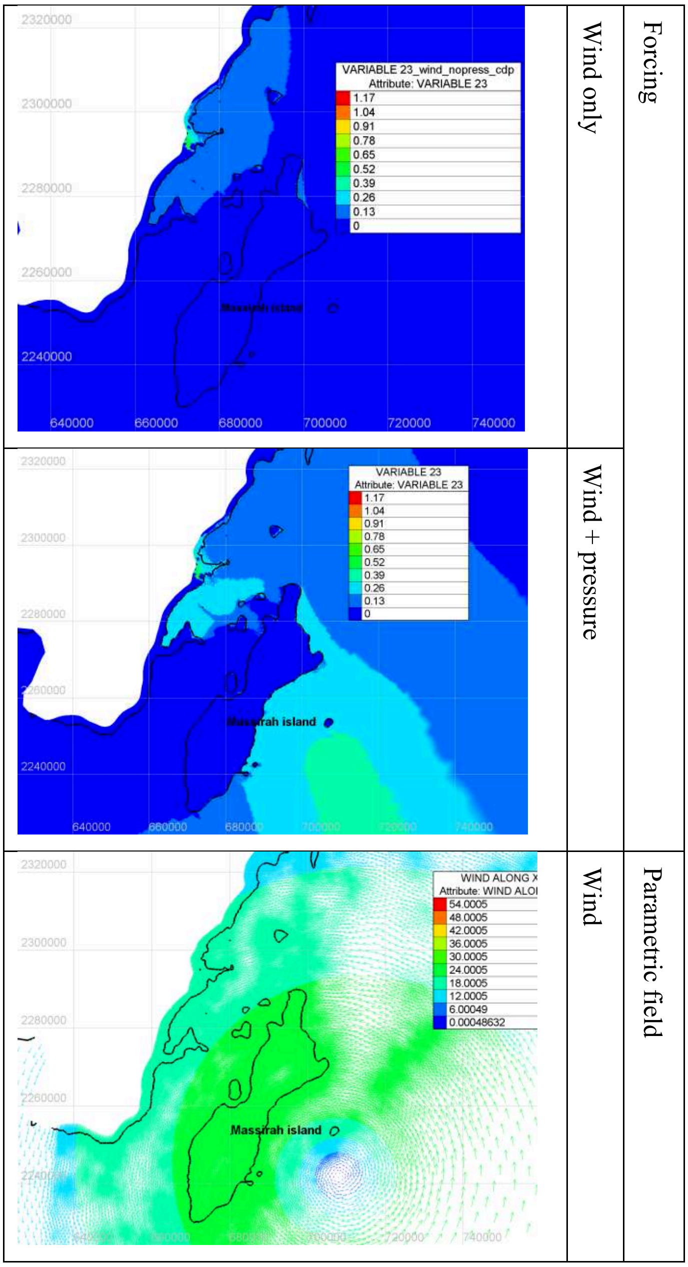

Figure 7. Prediction of the Maximum Elevation Of Water and wind field on the 6th June 2007,16:00 under the impact of the wind only or the impact from the wind and atmospheric pressure. The solid black line depicts the MSL contour line or shoreline.

VII. Conclusion

Tropical cyclones are extreme moving events that can become a real threat when approaching the coast by bringing high winds and inducing inundation. This inundation is due to the combined effect of inverse barometer, wind setup, wave setup and runup and rainfall superimposed on the tide. Here we introduce a tool to create cyclone forcing fields for TELEMAC and TOMAWAC that enables the run of a past or synthetic cyclone. The tool proves to be useful to investigate and separate the inundation factors.

References

[1] Fritz, H.M., C. Blount, R. Sokoloski, J. Singleton, A. Fuggle, B.G. McAdoo, A. Moore, C. Grass, B. Tate (2007). Hurricane Katrina Storm Surge Distribution and Field Observations on the Mississippi Barrier Islands, Estuarine, Coastal and Shelf Sciences, 74(1-2):12-20, doi:10.1016/j.ecss.2007.03.015.

[2] Fritz, Hermann & Blount, Christopher & Albusaidi, Fawzi & Al-Harthy, Ahmed. (2010). Cyclone Gonu Storm Surge in the Gulf of Oman. 10.1007/978-90-481-3109-9_30.

[3] Fritz, Hermann & Naderi Beni, Abdolmajid. (2015). Comparison between the 2007 Cyclone Gonu Storm Surge and the 2004 Indian Ocean Tsunami in Oman and Hormozgan, Iran. Fifth International Conference on Estuaries and Coasts (ICEC2015), November 2-4, 2015, Muscat, Oman.

[4] Hassannezhad, M., Soltanpour, M., & Haghighi, S. (2011). 2D Hydrodynamic Modeling and Measurements of Chabahar Bay. Journal of Coastal Research, 1043–1047.

[5] Allahdadi, Mohammad Nabi, Chaichitehrani, Nazanin, Jose, Felix, Nasrollahi, Ali, Afshar, Ami, Allahyar, Mohammadreza (2018) Cyclone-generated Storm Surge in the Northern Gulf of Oman: A Field Data Analysis during Cyclone Gonu, American Journal of Fluid Dynamics, Vol. 8 No. 1, 2018, pp. 10-18. doi: 10.5923/j.ajfd.20180801.02.

[6] Soltanpour M, Dibajnia M. Field Measurements and 3D Numerical Modeling of Hydrodynamics in Chabahar Bay, Iran. ijmt. 2015; 3 :49-60 URL: http://ijmt.ir/article-1-226-en.html

[7] Al-Buloshi A, Al-Hatrushi S, Charabi Y (2014) GIS-based Framework for the Simulation of the Impacts of Sea Level Rise and Coastal Flooding on Oman. J Earth Sci Clim Change 5: 238. doi:10.4172/2157-7617.1000238

[8] Knapp, K.R., Kruk, M.C., Levinson, D.H., Gibney, E.J., 2009. Archive compiles new resource for global tropical cyclone research. EOS 90, 46.

[9] Holland, G. (1980). "An Analytic Model of the Wind and Pressure Profiles in Hurricanes". Monthly Weather Review. Volume 108. 1212-1218.

[10] Dibajnia, M., Soltanpour, M., Scott, D. (2009) An assessment of climate change impact on cyclone frequency and design wave height in the oman sea. In 1st WMO international conference on tropical cyclones and climate change (WWRP 2010 – 2), Muscat, Sultanate of Oman, 8 – 11 March 2009, Edited by: Salim Al-Hatrushi and Yassine Charabi Department of Geography Sultan Qaboos University, Muscat, Sultanate of Oman

[11] National Center of Meteorology and Seismology of United Arab Emirates, Abu Dhabi (2007) Gonu, the tropical storm.

[12] Hajivalie, Fatemeh & Arabzadeh, Ahmad. (2017). A 3D Numerical Study of Cyclone Gonu Waves Impact on Ramin Port. International Journal of Coastal and Offshore Engineering. 1. 33-41. 10.18869/acadpub.ijcoe.1.1.33.

[13] Garrat J.R. (1977) Review of drag coefficient over oceans and continents. Monthly Weather Review, American Meteorological Society