ICFM6
6TH INTERNATIONAL CONFERENCE ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

A PRACTICAL MULTI-MODEL APPROACH FOR COASTAL FLOODING DUE TO TROPICAL CYCLONES

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ABSTRACT: The modeling of coastal flooding due to tropical cyclones (TCs) is a challenge involving meteorologists, oceanographers, coastal engineers and hydrologists. Each element (wind, sea level pressure, waves, surge, tide, response of coastal defences, run-off, river discharges) can be addressed with a different degree of complexity, regarding the physical processes involved and the spatial resolution. A key issue is to balance the different components, obtaining an efficient, robust and manageable method composed by a number of numerical and empirical models capable of being applied for the reconstruction of past TCs and also for the synthetic generation of possible TCs. In this work, we propose a method based on the combination of a suite of atmospheric, hydrologic and hydrodynamic models. The methodology is applied to evaluate the coastal flooding associated to TC Gonu (June 2007) in Muscat (Oman), validating the results obtained qualitatively (pictures, satellite imagery) and quantitatively (buoys, tidal gauges).

Key Words: Astronomical Tide, Gonu, Storm Surge, Wadis, Waves

1. INTRODUCTION

Tropical cyclones (TCs) hitting the coast can produce extensive damages associated with wind and flooding. In particular, the coastal flooding is the result of the interaction between marine dynamics (astronomical tide, storm surge, mean sea level), local precipitation and river discharges (or wadis), see the study area in Figure 1. Each physical process (wind, sea level pressure, waves, surge, tide, response of coastal defenses, run-off, river discharges) can be addressed with a different degree of complexity depending on its type and spatial resolution. The objective of this work is to propose a framework able to estimate the statistical distribution of coastal flooding in areas affected by both regular (RMC) and tropical cyclone (TCC) marine climate conditions and to apply the suite of models to a particular case in Muscat, the capital of Oman, to reproduce the coastal flooding associated to TC Gonu in June 2007.

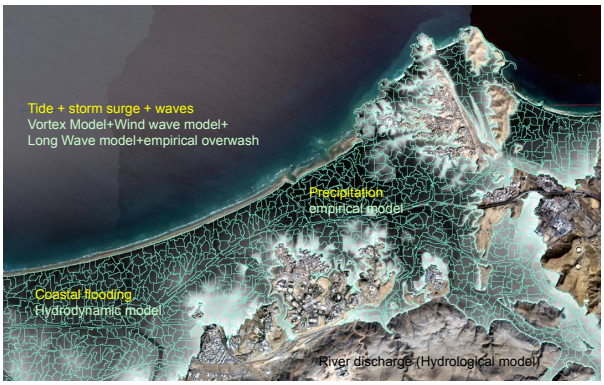

Figure 1. Drivers that generate coastal flooding due to TCs in Muscat (Oman)

2. METHODOLOGICAL FRAMEWORK

Coastal flooding risk characterization in the Omani coast depends on both regular (RMC) and tropical cyclone (TCC) marine climate conditions. Sporadically, the Omani coast suffers the impact of major tropical cyclones (TCs) that affect dramatically the statistical distribution of the hazard. As these events are very rare, it is essential to reconstruct past TC events and also to generate synthetically possible future TCs. Figure 2 shows a flow chart of the methodology developed to obtain the statistical distribution of coastal flooding. The objective is to develop an efficient, robust and manageable method comprising several numerical and empirical models, balancing the complexity and accuracy of the different elements involved. An important part of this methodological framework is the validation using any kind of information available (in situ evidences, newspapers, imagery from satellite, etc).

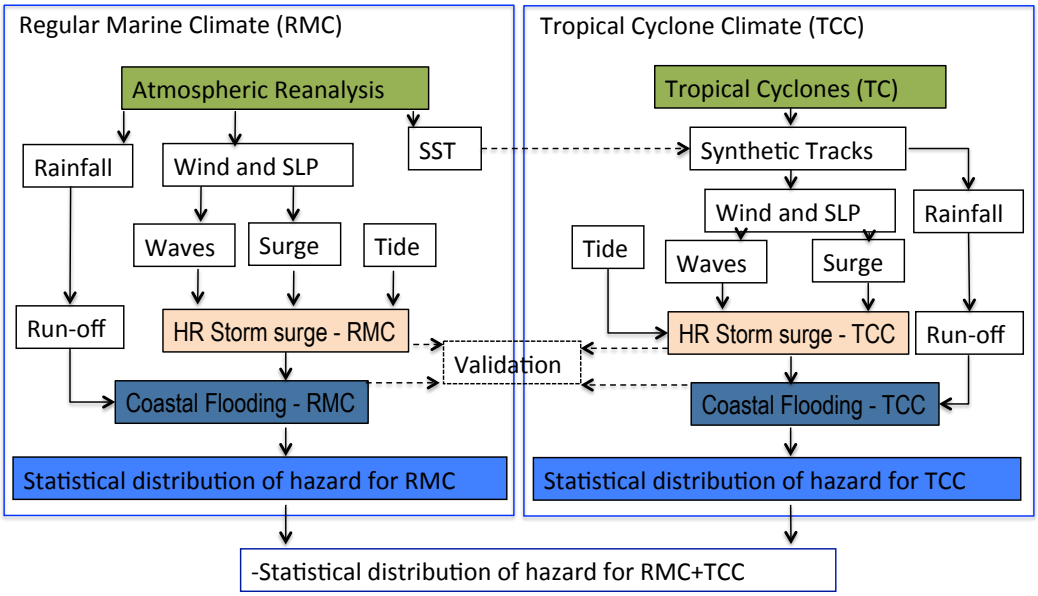

Figure 2. Flow chart of the methodology combining a suite of stochastic, atmospheric, hydrologic and hydrodynamic models

The marine component (Total Water Level, see Figure 3) is composed of different elements (i.e., astronomical tide and the storm surge levels associated to pressure-wind and to wind waves (dynamic wave set-up generated by the radiation stress gradients). Nowadays there are different suites of models (ADCIRC+SWAN, COAWST, Delft3D) able to solve all the processes together and taking into account all the non-linearities involved. In our approach, we linearly split up the three components AT, SSL_PW and SSL_H, modeling them separately.

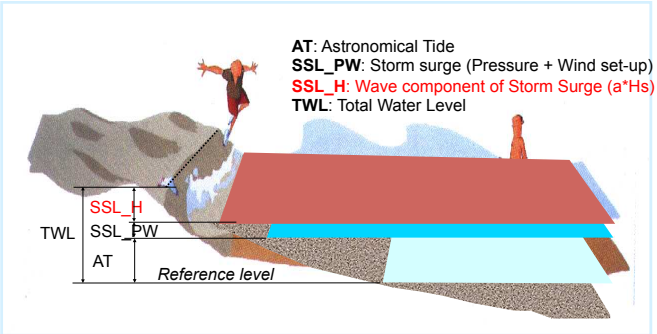

Figure 3. Sketch of the different components that affect coastal flooding

3. DATA

We use regional bathymetry from ETOPO 1 min spatial resolution and nautical charts covering the Omani coast. Regarding the topography in Muscat, a high resolution digital elevation model (5 m) is used. It is important to note that the success of the coastal flooding modeling strongly depends on the quality and accuracy of the digital elevation model, in particular in the interface between land and sea. Small errors (in vertical) can lead to important biases in the results, reinforcing the necessity of balancing the accuracy of the flooding models and the topography.

Wind and sea level pressure fields are obtained from the Climate Forecast System Reanalysis (CFSR, Saha, 2010). This data base has been generated by the National Center for Environmental Prediction (NCEP) covering 31-years in the period 1979-2010. Spatial and temporal resolution is 0.3º and 1 hour, respectively. Although this atmospheric reanalysis is able to capture tropical cyclones, the intensity is not well modeled. For that reason, we use the tropical cyclone best track data base IBTrACS (International Best Track Archive for Climate Stewardship) and an empirical vortex model, based on Holland (1980) Figure 3 shows an example of the merging of both data bases to define the spatial and temporal fields of winds (shown in the figure) and sea level pressure.

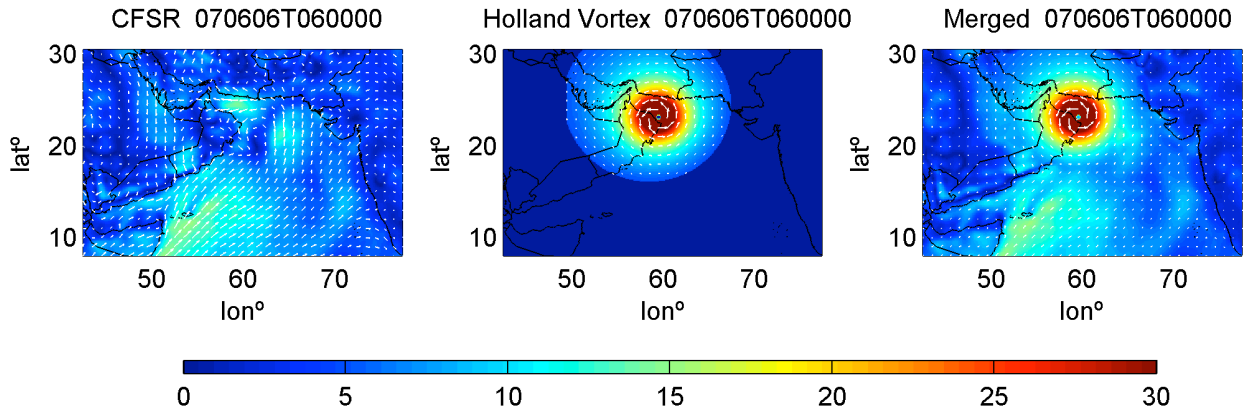

Figure 4. Wind field from CFSR atmospheric reanalysis and from Vortex model (m/s) during TC Gonu (2007)

Astronomical tide has been simulated using the Regional Ocean Model System (ROMS) developed by Rutgers University (Shchepetkin and Mcwilliams, 2005). ROMS is a 3D free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation. In this study, ROMS is run in barotropic mode. Harmonic constituents are obtained from TPXO7.2 model (Egbert and Erofeeva, 2002) at a 0.25º spatial resolution. Figure 5 shows the good agreement of the tidal elevations of the model in Muscat tidal gauge. The small differences are associated to the reduced number of components (13) of TPXO7.2 model.

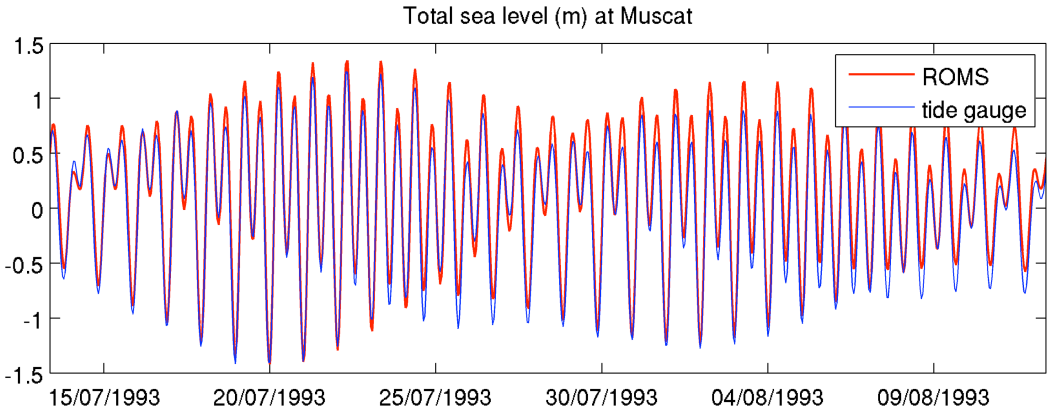

Figure 5. Validation of Tidal Elevation model in Muscat

4. MODELS

4.1 Wind wave model

In this work, we have used the SWAN model (Simulation Waves Nearshore, Booij et al 1999). SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in open seas and coastal regions. This model accounts for the following physics: wave generation by wind, wave propagation in time and space, shoaling, refraction, three- and four-wave interactions, whitecapping, bottom friction, depth-induced breaking, wave-induced set-up, wave generation and propagation at regional scales, transmission through and reflection against obstacles and diffraction. In our work, we have defined a 10 Km spatial resolution grid in the Arabian sea and a 1 Km grid in Muscat area (see Figure 6). Figure 7 shows the time-series of different sea state parameters (significant wave height, mean period, mean direction) in the vicinity of Muscat for the year 2010. As can be seen only one stormy event exceeding 4m Hs has been registered on this year, showing the importance of modeling both the RMC and TCC.

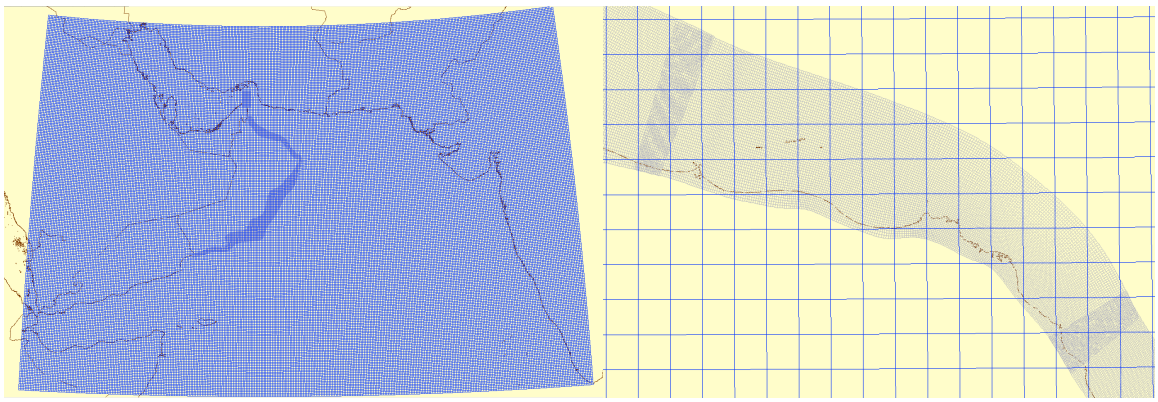

Figure 6. Regional (10 Km spatial resolution) and local (0.5-1 Km) wind wave grids. Detail in Muscat area

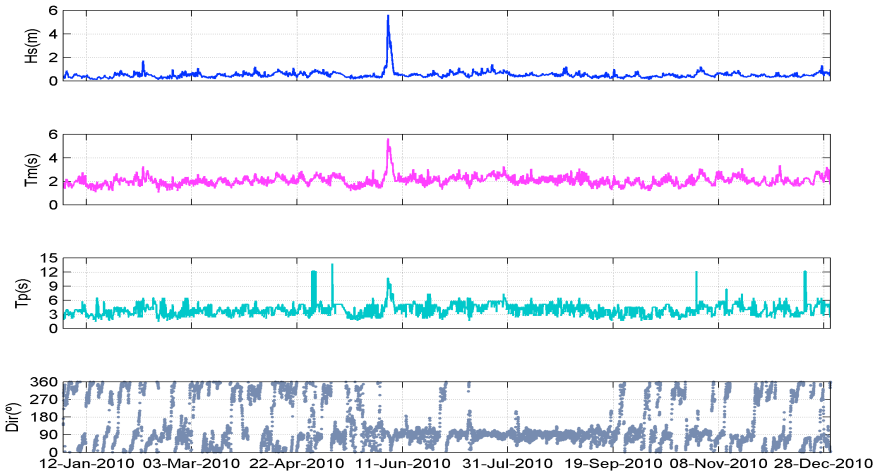

Figure 7. Example of time series of sea state parameters evolution in Muscat during 2010. The intensity of the event in June 2010, is of particular note and is due to tropical cyclone Phet.

4.2 Storm surge model

We use the ROMS model (Shchepetkin and Mcwilliams, 2005) forced with the wind and sea level pressure fields calculated from CFSR and the vortex model. The spatial resolution of the grid is 10 Km and we use the inverted barometer as a boundary condition. The simulation of Gonu is shown in Figure 8. Panels show the envelope of maximum storm surge levels using ROMS (left) and significant wave height using SWAN (right). The maximum values of the storm surge component due to wind and pressure in Muscat is about 1m. On the other hand, maximum values of significant wave height at Muscat area is about 10m. Assuming that wave set-up is approximately 20% of significant wave height (Guza and Thornton, 1981; Nielsen, 1988, Stockdon et al, 2006), the wave-induced storm surge contribution is about 2m. These findings are highly relevant, showing that the wave-induced water level variations in the surf zone can be more important than the wind-pressure storm surge, as pointed out by Fritz et al (2010).

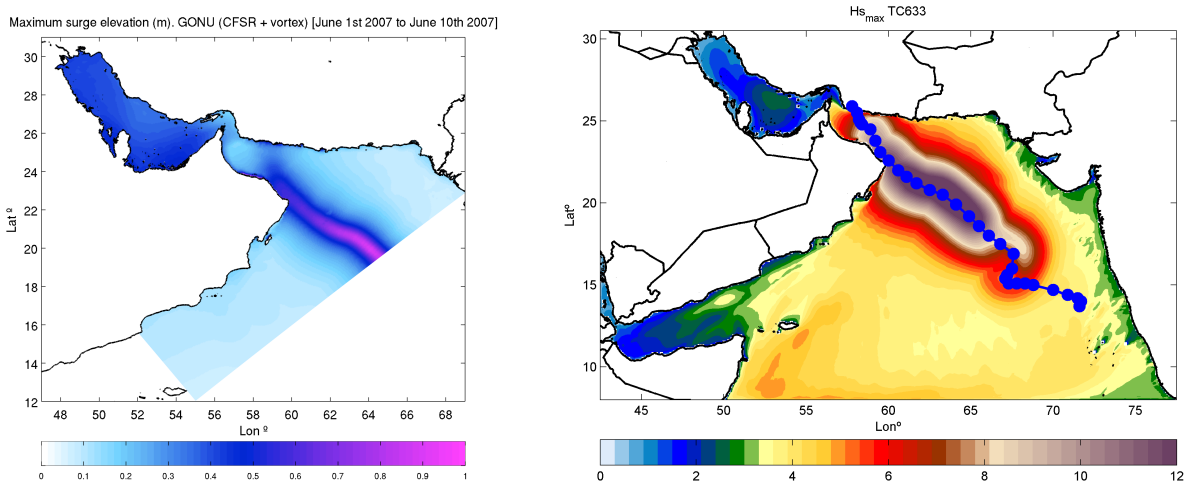

Figure 8. Envelope of maximum storm surge levels (left) and significant wave height (right) during TC Gonu (2007). Units are in m.

4.3 Total water level reconstruction

Following the sketch of Figure 3, the next step is to linearly add in the time domain the different contributions to total water level, *TWL(t)=AT(t)+SSL_WP(t)+SSL_H(t)*. These time series are calculated at the location of the coastal defences, and define the boundary conditions of the coastal flooding model (see some of the reconstructed time series in Figure 9 for TC Gonu in Muscat). Note that in our approach we split up the problem of coastal flooding in two elements: 1) large scale marine component; and 2) high resolution coastal flooding. The benefits of this approach is that is much more efficient in terms of computational resources and allow a detail description of the probability of failure of the coastal defences (Gouldby et al, 2008).

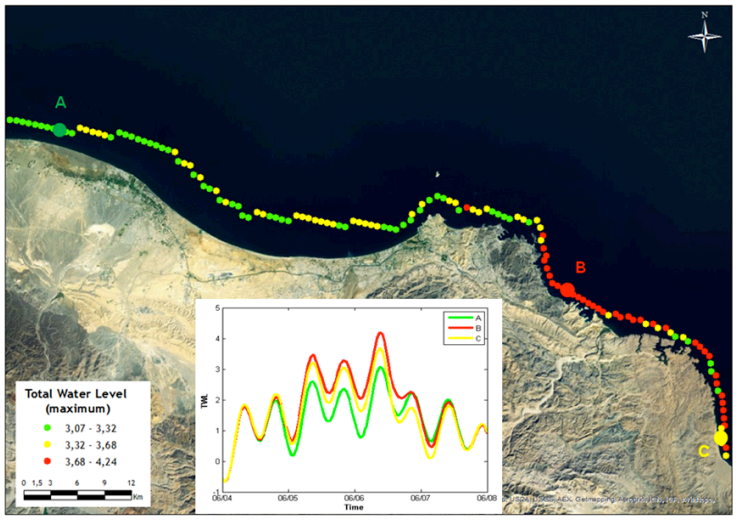

Figure 9. Temporal and spatial distribution of total water level in Muscat during Gonu (2007). Units are in m

4.4 Coastal flooding model

The model selected to simulate coastal water inundation into mainland on a local scale is RFSM-EDA (Rapid Flood Spreading Method – Explicit Diffusion with Acceleration term). RFSM-EDA is a 2D inundation model developed by HR Wallingford (Jamieson et al, 2012). RFSM-EDA is based on a diffusive approximation of the shallow water equations. It differs from many simplified diffusive wave models by incorporating an additional term – the local acceleration (or local inertia) term, which provides increased stability and faster runtimes (Bates et al, 2010). It has the capability of running efficiently at different spatial scales, providing water depths over ground and velocity outputs with short run times. Its algorithm allows to account for the key topographic features such as crests and low points derived from a high resolution digital terrain model, by using relatively large computational elements or tesellas (see the discretization of the cells in Figure 1).

The simulation of Gonu in Muscat has been carried out with a total duration of 96 hours, starting 2 days before the peak of the storm (see Figure 10). The hydrographs from the marine dynamics are defined at the boundaries every 500 m (dots in Figure 9) and, on the other hand, the inflows from the wadis are calculated using a modified version of the hydrological model CUENCAS (Cunha et al 2010), forced with data from TRMM radar rainfall data base.

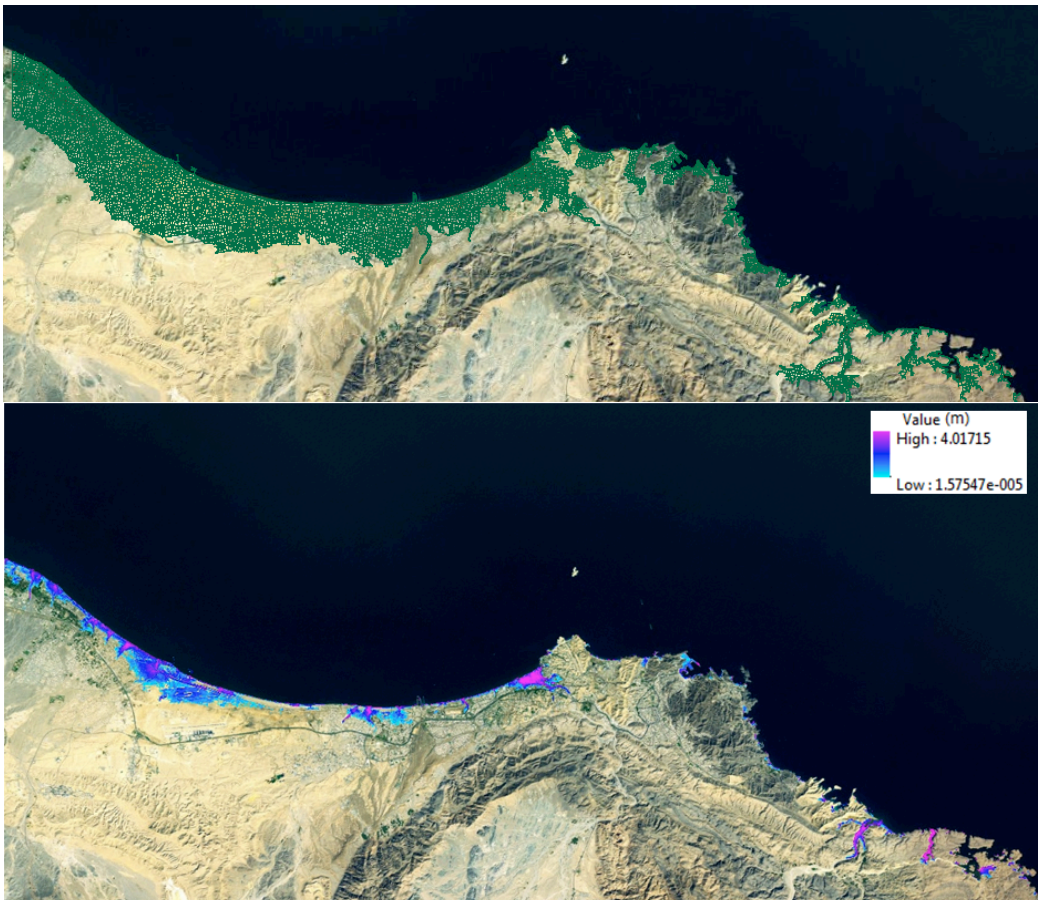

Figure 10. (Upper) Details of the grid with average size of 0.04 Km^2. (Lower) Simulation of coastal flooding depths caused by Gonu (2007).

Fritz et al (2010) conducted an extensive field data campaign to estimate higher water marks in the different areas affected by tropical cyclone Gonu. We have used these data to validate our results (only 3 points are located in the low-lying areas in our domain, see left part of figure 11). This preliminary validation shows the ability of the suite of models that we have applied in this study. Moreover, in order to have a spatial validation, we have compared our results with a Landsat 7 image taken 3 days after the peak of the storm, in which we have applied an algorithm to identify the wet areas (see right part of Figure 11). As seen, the model and the observations are in agreement qualitatively.

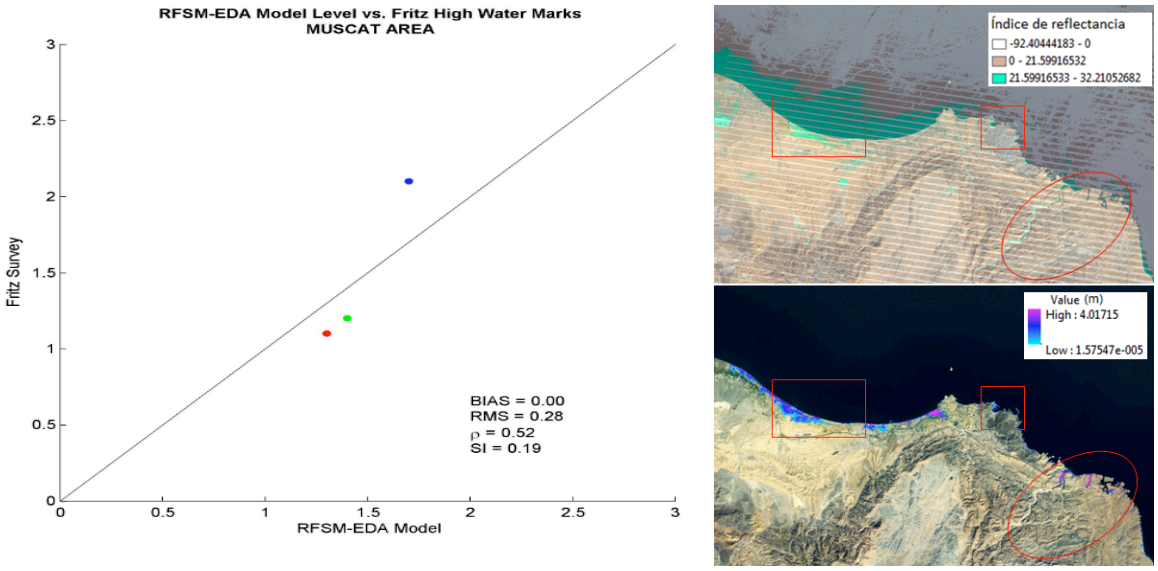

Figure 9. (Left) Comparison between model and measured high water marks (from Fritz et al 2010), units in m. (Right) Maximum depths from model and from Landsat 7 satellite imagery.

5. CONCLUSIONS

A multi-model approach has been developed to estimate the statistical distribution of flooding (flooding depths and flooding extents) in low-lying coastal areas affected by tropical cyclones. The model is composed of different modules that are interlinked trying to be well-balanced in the different elements. The decomposition into different modules, according to the regular marine climate and to the tropical cyclone climate, allows analysis of the uncertainty associated with each component and a probabilistic risk assessment can be undertaken in a practical way.

We have applied the methodology to model the coastal flooding in Muscat (Oman) due to tropical cyclone Gonu (June, 2007). The results have been validated with in situ observations and qualitatively with satellite imagery from Landsat 7.

6. REFERENCES

Bates, P.D., Horritt, M.S., Fewtrell, T.J., (2010). 'A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling'. Journal of Hydrology 387(1–2): 33–45.

Booij, N., Ris, R. C. and Holthuijsen, L. H. (1999). "A third-generation wave model for coastal regions: 1. Model description and validation." *Journal of Geophysical Research: Oceans* 104(C4): 7649-7666.

Cunha et al (2012) Impact of radar-rainfall error structure on estimated flood magnitude across scales: An investigation based on a parsimonious distributed hydrological model, *Water Res. Res.*, DOI: 10.1029/2012WR012138

Egbert, G. D., & Erofeeva, S. Y. (2002). Efficient Inverse Modeling of Barotropic Ocean Tides. Journal of Atmospheric and Oceanic Technology, 19(2), 183–204

Fritz, H.M., Blount, C.D., Albusaidi, F.B.. and Al-Harthy, A.H.M., (2010). 'Cyclone Gonu storm surge in Oman'. Estuarine, Coastal and Shelf Science 86 (2010) 102-106.

Gouldby, B., Sayers, P., Mulet-Marti, J., Hassan, M. and Benwell, D., (2008). 'A methodology for regional-scale flood risk assessment'. Proceedings of the Institution of Civil Engineers- Water Management 161(3): 169–182.

Guza, R. T. and E. B. Thornton (1981),Wave Set-up on a Natural Beach, Journal of Geophysical Research, Vol.96, No. C2, pp.4133-4137

Holland, G.J., (1980). "An analytical model of the wind and pressure profiles in hurricanes". *Mon. Wea. rev*. 180, 1212–1218.

Jamieson, S., Lhomme, J., Wright, G. and Gouldby, B. (2012). "A highly efficient 2D inundation model with sub-element topography." *Proceedings of the ICE - Water Management*, Volume 165, Issue 10.

Nielsen, P. (1988). Wave Setup: A Field Study, Journal of Geophysical Research , Vol. 93(C12), pp.15,643-15,652

Saha, Suranjana, et. al., 2010. The NCEP Climate Forecast System Reanalysis. Bull. Amer. Meteor. Soc., 91(8), 1015-1057 (DOI: 10.1175/2010BAMS3001.1).

Stockdon, H.F.,R.A. Holman, P.A. Howd, and A.H. Sallenger, Jr. (2006). Empirical Parameterization of Setup, Swash, and Runup, Coastal Engineering 53 573-588, Elsevier Publishing, the Netherlands.

Shchepetkin, A. F., and J. C. Mcwilliams (2005), The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, *Ocean Modelling*, 9(4), 347–404, doi:10.1016/j.ocemod.2004.08.002.