TOWARDS AN OPERATIONAL FORECAST MODEL FOR COASTAL INUNDATION DUE TO STORM SURGES: APPLICATION DURING IANOS MEDICANE

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ABSTRACT

This paper presents the application of a numerical model (CoastFLOOD) for the simulation of coastal inundation due to storm surges enhanced by tides. The implementation is based on output of sea level elevation caused by the combined action of storm surges and astronomical tides from operational forecasts with High Resolution Storm Surge (HiReSS) model in the Mediterranean Sea. The presented case study of coastal inundation refers to the littoral floodplain of Livadi coastal inlet at the island of Cephalonia (central Ionian Sea, western Greece), induced by the passage of Ianos Medicane (with Category 2 Hurricane characteristics) in September of 2020. Validation of storm-induced sea level elevation against *in situ* data by tide gauges is also presented *in tandem* with estimations of flooded areas over coastal lowlands. The latter are compared with satellite observations (Sentinel-2 images) producing the Normalized Difference Water Index (NDWI). The seawater run-up extended up to several hundreds of meters inland, depending on hydraulic connectivity between lowland areas, which determined the inundation extents during the storm surge events.

Keywords: coastal inundation, storm surge, Ianos Medicane, operational forecast, numerical modelling

1. INTRODUCTION

The Mediterranean Sea is considered to be a hotspot in reference to impacts of extreme weather events on the coastal zone. Intense storm surge events might threaten lowland coastal areas mainly by inundation effects on littoral floodplains which may cause human casualties, land loss, damages to onshore infrastructure and properties, environmental degradation, etc. Therefore, in the present work, a new coastal inundation module (CoastFLOOD) [1] is implemented in operational forecast/hindcast modes coupled to a tidally enhanced storm surge model (HiReSS) [2] for the proper simulation of large scale storm-induced coastal flooding. The Ianos Medicane [3] case study is investigated in terms of invoked coastal inundation on the littorals of coastal inlets at the island of Cephalonia (central Ionian Sea, western Greece). For this, numerical, in situ, satellite, and GIS land elevation data are combined.

2. METHODOLOGY

Extremely deep atmospheric depressions in the synoptic scale on the Mediterranean basin usually lead to the formation of storm surges on the coastal boundary in local scale, due to two main mechanisms: i) the inverse barometer effect underneath the low-pressure area of the cyclone, and ii) the wind-induced accumulation of seawater masses towards the coast.

2.1. Available Data (Atmospheric Input, GIS Land Elevation, Field and Satellite Observations)

Ianos Medicane, with characteristics similar to a Category 2 hurricane (wind gusts of 160 km/h), propagated over the central Mediterranean in mid-September 2020 [3] and induced damages on both inland and coastal areas, in central and western Greece (Ionian islands and continental coasts), causing extensive flooding, infrastructure destructions, and human casualties. The meteorological forcing is derived from two sources: a) the Numerical Weather Prediction (NWP) system of Aristotle University of Thessaloniki (LMC-AUTH) [4], b) gridded operational analyses of the European Centre for Medium-range Weather Forecasts (ECMWF), employed in forecast and hindcast mode simulations, respectively. Land elevation data were derived by post-processing of available geospatial data from the Digital Elevation Model (DEM) of Hellenic Cadastre (https://www.ktimatologio.gr/en), with a pixel size of 2×2 m^2 available in 4600×3600 m^2 ground plates, with a perimeter overlay of 300 m, in GGRS87 projection. Field measurements of sea level elevation have been collected by available tide-gauge sensors along the coasts of the Ionian Sea, freely provided in 1-minute time-step by the Sea Level Station Monitoring Facility of the Intergovernmental Oceanographic Commission (https://www.iocsealevelmonitoring.org/). The measured data are used to validate the performance of the numerical hydrodynamic simulations and estimate the realistic storm surge intensity during IANOS Medicane [3].

2.2. Numerical Models for Storm Surge and Coastal Inundation

The sea level conditions and characteristics during the Ianos passage over the affected coastal regions were investigated with the use of HiReSS, a 2-D hydrodynamic model for barotropic circulation [2], operating in both forecast and hindcast modes [5]. Herein, we focus on the sea level response due to severe meteorological conditions that mainly determined the ocean circulation and coastal sea level variability during a extreme low-pressure system [6]. HiReSS can predict the Sea Level Anomaly (SLA) and depth-integrated currents, induced by atmospheric forcing, combined with astronomical tide effects [5, 6], being the tool of several operational forecast applications in the Mediterranean Sea (Wave4Us) [7] and around the world (Accu-Waves) [8].

CoastFLOOD [1] is a very high resolution, GIS raster-based, 2-D horizontal, mass balance, coastal inundation model, which is based on the concepts of the established LISFLOOD-FP software [9] for coastal plain flooding on a local scale over selected areas of the littoral land zone in Greece, pertaining parts of urban environment and engineered waterfronts, ports and coastal structures, estuaries, adjacent lagoons, and natural beaches [1]. It is one-way coupled to HiReSS model, fed with output of simulated sea level data as boundary conditions representing the study area's coastline. We hereby combine this approach with a wet/dry cell assignment technique for flood fronts over steep slopes [10]. The flood routing module makes use of a very fine spatial resolution ($dx = dy = 2$ m) computational domain based on DEM raster grids (see Section 2.1). CoastFLOOD also incorporates a "static-level" inundation module operating in "bathtub" mode with or without hydraulic connectivity [11, 12].

3. RESULTS

3.1. Model Validation

Figure 1 shows the validation of HiReSS model outputs in operational forecast and hindcast modes against field data of SLA for the Ianos Medicane period. Acceptable to rather high Pearson correlations and coefficients of determination were found, indicating the good model performance in coastal areas.

3.2. Flooded Areas

Maps of Flooded Areas are presented in Figure 2 derived from CoastFLOOD simulations by simple Bathtub, Bathtub with Hydraulic Connectivity (HC), and realistically simulated, Manning-type, inundation flow. The comparison between flood patches by CoastFLOOD model and Sentinel-2 NDWI reveals significant storm-induced run-up of seawater in specific parts of the coastal zone (200 m inland), in agreement with the "wet" areas derived from satellite imagery. Table 1 presents numerical data related to the inundated area (>$6{\cdot}10^5$ m^2).

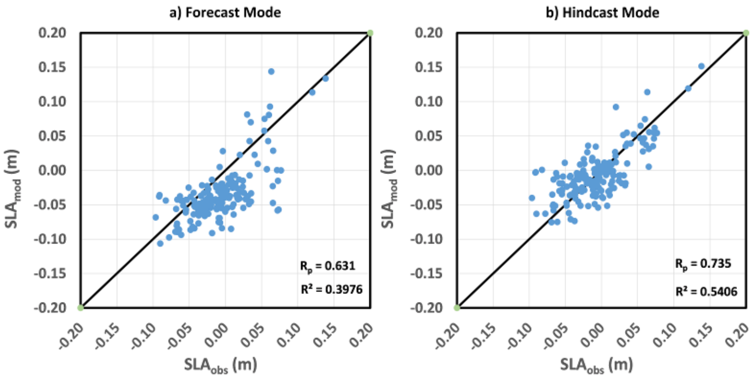

Figure 1. Scatter diagrams of comparisons between HiReSS modelled and field data of SLA (SLA$_{mod}$ and SLA$_{obs}$, respectively) for September 2020; a) WRF/ARW-fed HiReSS model results in operational forecast mode; b) ECMWF-fed HiReSS model results in hindcast mode. R$_P$: Pearson correlation, R^2: Coefficient of determination.

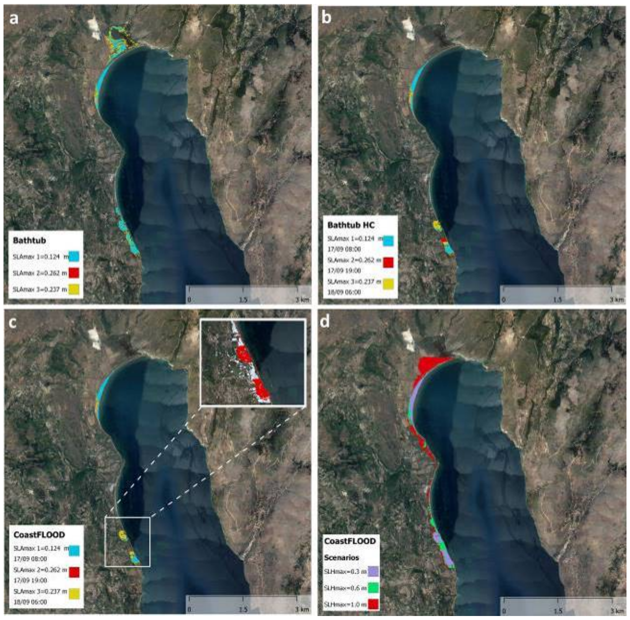

Figure 2. Maps of Flooded Areas derived from 3 CoastFLOOD approaches: (a) simple Bathtub, (b) Bathtub with Hydraulic Connectivity (HC), and (c) realistically simulated inundation Manning-type flow for three characteristic cases (SLA$_{max1\text{-}3}$ = 0.124, 0.262, 0.237 m) of IANOS passage over the study area. (d) Potential Flooded Area derived from CoastFLOOD simulations based on three extreme scenarios of storm surge (0.3, 0.6, 1.0 m). Comparison between flood patches by CoastFLOOD model (red hatch) and satellite NDWI ("wet" areas with light blue) is shown in panel c insert.

Table 1. Features of flooded lowlands in the study region: Elevation Class, Total Area (m^2), Normalized Difference Water Index (NDWI) Mean Difference, Flood Difference (m^2), coverage percentage of Flood (%).

Elevation Class	Total Area (m^2)	NDWI Mean Difference	Flood Difference (m^2)	Flood (%)
0 m - 0.3 m	631,556	0.10490	17,168	2.7

4. CONCLUSIONS

A model for coastal flooding simulations fed by an ocean hydrodynamics model *in tandem* with field and satellite observations was used to describe the storm surge-induced coastal inundation processes due to the impact of Ianos Medicane in September 2020. The improvement of atmospheric forcing increases the efficiency of the coastal sea level predictions and thus the quality of littoral flooding estimations. The nested numerical methodology may provide short-term and real-time predictions of the flooding status on a coastal scale, useful to local first level responders during extreme meteorological events.

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