Severe Weather Events and Sea Level Variability Over the Mediterranean Sea: The WaveForUs Operational Platform

Y. Krestenitis, I. Pytharoulis, Theodore S. Karacostas, Y. Androulidakis, C. Makris, K. Kombiadou, I. Tegoulias, V. Baltikas, S. Kotsopoulos and S. Kartsios

Abstract The storm surge, i.e. sea-level elevation due to severe atmospheric conditions (strong winds and low pressures), is a major factor of coastal inundation that can induce significant problems over low-land areas. 'WaveForUs' is a high-resolution forecasting system for public and emergency use that delivers meteorological and sea-state predictions over the Mediterranean Sea (0.15°). The results of a 2-D hydrodynamic model, that simulates the sea-surface elevation due to the combined effect of atmospheric forcing (pressure and wind) and astronomical tides, are used to estimate the total surge along the coasts. The meteorological model used is the Weather Research and Forecasting model with the Advanced Research dynamic solver. We investigate the relation between extreme surge events and the atmospheric low-pressure systems during two severe weather events that appeared in the 2013–2015 period. Comparisons with the available satellite and in situ observations and gridded analyses show the good performance of the operational system. The morphological changes over a coastal region (e.g. orientation, existence of straits and islands) play an important role on the storm surge variability during a severe atmospheric low-pressure event. The seasonal variation of both weather storms and storm surges during the study period is also under investigation.

1 Introduction

Coastal flooding as a result of storm surge events is a possible threat in Mediterranean coasts. Storm surges are a result of low pressure meteorological systems. WaveForUs (Wave climate and coastal circulation Forecasts for public

Y. Krestenitis (✉) · Y. Androulidakis · C. Makris · K. Kombiadou · V. Baltikas
Laboratory of Maritime Engineering and Maritime Works, Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
e-mail: ynkrest@civil.auth.gr

I. Pytharoulis · T.S. Karacostas · I. Tegoulias · S. Kotsopoulos · S. Kartsios
Laboratory of Meteorology and Climatology, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece

T.S. Karacostas et al. (eds.), *Perspectives on Atmospheric Sciences*,
Springer Atmospheric Sciences, DOI 10.1007/978-3-319-35095-0_9

Use; http://wave4us.web.auth.gr) is a newly implemented forecasting system that uses state-of-the-art atmospheric and storm surge modeling in order to produce daily, user-friendly 3-day sea state forecasts in Mediterranean Sea, Aegean Sea and Thermaikos Gulf and deliver them to users through television, internet and GIS applications. The meteorological forecasts of the Weather Research and Forecasting (WRF) model for the three domains (Pytharoulis et al. 2015) are created operationally and are offline coupled to the sea state models. The results of a 2-D hydrodynamic ocean model (HRSS; Krestenitis et al. 2010; Androulidakis et al. 2015) that simulates the free surface elevation are used to estimate the total surge distribution over the three domains in a daily basis.

2 Methodology

2.1 Atmospheric Model

The non-hydrostatic WRF model (version 3) with the Advanced Research dynamic solver is integrated in three telescoping nests which cover Europe and the Mediterranean basin, the central and eastern Mediterranean Sea and the northern Greece—Thermaikos Gulf with horizontal grid-spacings of 15, 5 and 1.667 km, respectively. 39 sigma levels, up to 50 hPa, are used in the vertical direction. The initial and boundary conditions are based on the operational NCEP/GFS analyses and 3-hourly forecasts of the 12:00 UTC cycle, with a grid-spacing of 0.5° × 0.5° (lat.-lon.) until the summer of 2015 and 0.25° × 0.25° since then. The high resolution (1/12° × 1/12°) sea-surface temperatures of NCEP are employed by the model and are kept fixed throughout the 96-h forecast horizon. The Ferrier, Betts-Miller-Janjic, Mellor-Yamada-Janjic and RRTMG schemes parameterize the microphysical processes, sub-grid convection, boundary layer and radiation respectively, while the NOAH Unified Model represents the soil processes.

2.2 Ocean Model

The HRSS hydrodynamic model is applied in Mediterranean Sea, Aegean Sea and Thermaikos Gulf with a step of 0.15°, 0.05° and 0.016°, respectively. Atmospheric input parameters for the sea-state model are obtained by the application of WRF-ARW (Sect. 2.1). The main equations of the mathematical model are the momentum and continuity equations. The calculation of the wind stress fields is based on the transformation wind velocity data at 10 m, to the zonal/meridional components of the wind stress exerting on the sea surface. The contribution of the astronomical tide is calculated at every grid cell in the momentum equations, based on the Schwiderski (1980) parameterization.

3 Models Validation

The WRF forecasts of meteorological conditions in the Mediterranean Sea were evaluated against the ECMWF operational analyses (0.15° × 0.15°). The Mean Absolute Error (MAE) of the mean sea-level pressure (mslp) in the northern Adriatic Sea (not shown) ranges from about 0.95–1.0 hPa at 24 forecast hours to 2.15–2.2 hPa at 96 forecast hours. The MAE of the 10 m wind speed forecasts (not shown) over the latter area is about 1.6–1.7 m/s at 24 forecast hours and 2.3–2.4 m/s at 96 forecast hours. The daily output of the storm surge model were compared with respective available measurements from N. Adriatic Sea, an area that reveals significant extreme surges. Several model parameters were tested in order to increase the simulation-measurements comparison scores and improve the model performance (Krestenitis et al. 2015). The Root Mean Square Error (RMSE), the Pearson correlation (r) and the Willmot Skill Score (Ws) (Willmott 1981) are 0.10 m, 0.70 and 0.82 for Venice and 0.10 m, 0.70 and 0.79 for Trieste ($Ws \rightarrow 1$ and $r \rightarrow 1$ indicate perfect agreement of in situ and model series), showing the good performance of the forecasts (Fig. 1).

The meteorological model has been verified in all three domains during the operational period of Wave4Us project (Pytharoulis et al. 2015). The ocean model validation has also been done for all three domains (Krestenitis et al. 2015). However, the primary aim of this paper is to evaluate the performance of the modeling system in the Mediterranean Sea, and mainly in the vulnerable northern Adriatic Sea.

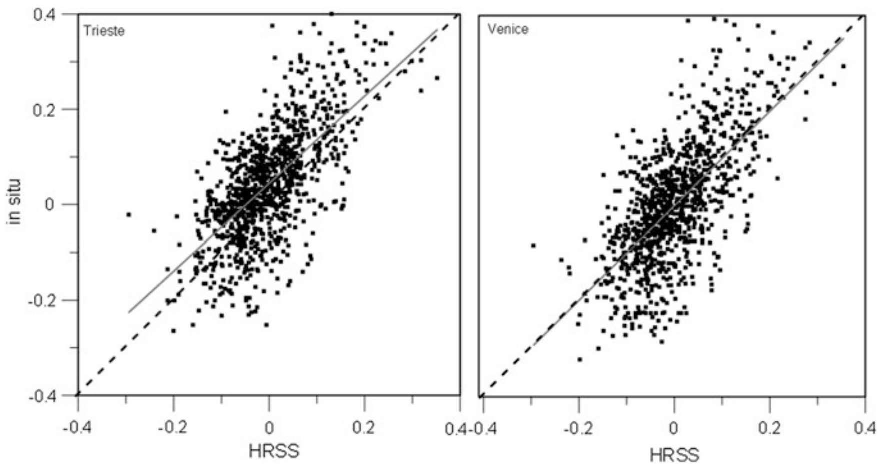

Fig. 1 Comparison between in situ and HRSS SLH (m) 2013–2015 time series in Trieste and Venice

4 Results and Discussion

4.1 *Extreme Events*

Several intense weather and surge events were captured by the simulations during the operational mode of the platform. Herein, we present a significant extreme storm surge event over Adriatic Sea (http://www.storm-surge.info) that appeared in late January and early February 2015 (Fig. 2). The surge affected the Venice Lagoon (~50 cm), causing extensive flooding in the city of Venice, while the SLH alteration of the eastern part of the region (Trieste) is 15 cm lower. The storm surge event of 30/1/2015 was attributed to a deep cyclone which affected Italy, with mslp below 980 hPa in the northern Adriatic Sea (Figs. 3 and 4) and a minimum mslp of 974 hPa at 12:00 UTC on the same day. On the other hand, the extreme surge a few days later, on 6/2 in Venice was due to the strong pressure gradient and the concomitant intense easterly-northeasterly winds (up to about 20 m/s), which prevailed in the northern Adriatic Sea (Fig. 4). These resulted from the combination

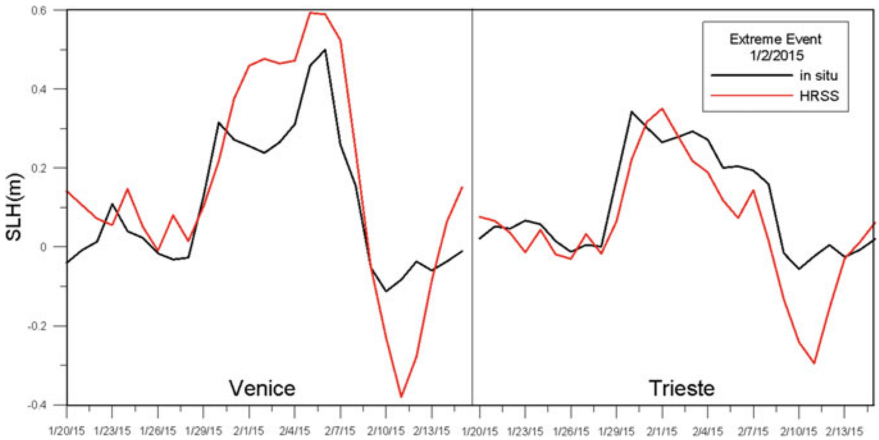

Fig. 2 Extreme storm surge event over Venice (*left*) and Trieste (*right*) on 1/2/2015

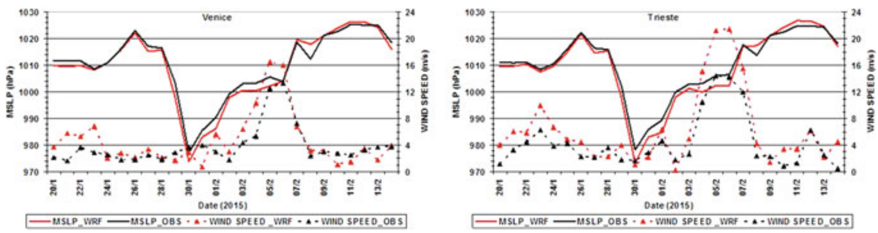

Fig. 3 Time series of daily mean predicted (WRF-D01, T+12–T+35 h) and observed wind speed at 10 m and mean sea-level pressure at Venice (45.51°N, 12.35°E) and Trieste (45.68°N, 13.75°E)

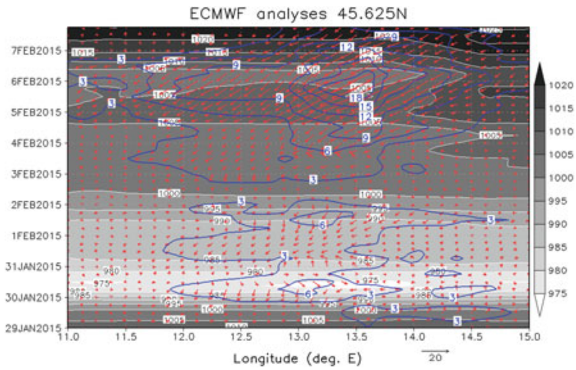

Fig. 4 Hovmoller diagram of mean sea-level pressure (*shading*; hPa), 10 m wind speed (*blue contours*; m/s) and direction (vectors) at 45.625°N (ECMWF analyses)

of high pressures in northern Europe and low pressure systems in the western and central Mediterranean Sea. The overestimation of SLH in Venice can be explained by the overestimated 10 m wind speed by WRF-D01 at both stations and mainly in its upstream area of Trieste (Fig. 3).

4.2 Seasonal Variability

The seasonal variability of storm surges varies between the Mediterranean sub-regions. The 95 percentile indicates the 5 % of high SLHs that may exceed a specific level (Fig. 5). The highest levels occurred over the Levantine basin, especially during winter. The spring levels are higher than the winter ones, over the westernmost Alboran Sea, indicating the strong spring events which appeared during spring months. Very high hourly percentiles (35 cm) also occur over Adriatic Sea.

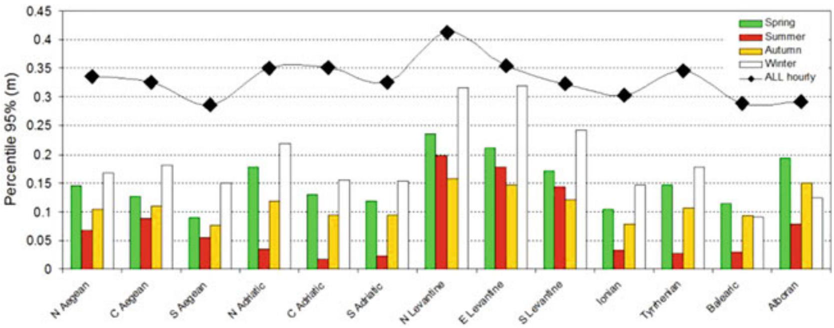

Fig. 5 Seasonal (*bars*) and hourly (*line*) percentile 95 of SLH (m) for several major Mediterranean subregions as derived from HRSS model during 2013–2015 forecasts

5 Conclusions

The ‘WaveForUs’ atmospheric and sea-state forecasting system was evaluated in the northern Adriatic sea during the operational phase of the project (2013–15) and two severe weather events associated with low pressure systems (January–February 2015). The forecasting system predicted the spatiotemporal variability of the storm surge during these events in good agreement with observations. The former event was associated with a very deep synoptic cyclone, while the second one (that was more intense) and its spatial variability were due to the gale force winds which resulted from the combination of high pressures in northern Europe and low pressure systems in the western and central Mediterranean Sea. The strongest extreme surge events appeared over the eastern Levantine Sea, especially during winter months.

Acknowledgments This study was co-financed by the European Union (European Regional Development Fund) and Greek national funds, through the action “COOPERATION 2011: Partnerships of Production and Research Institutions in Focused Research and Technology Sectors” (contract 11SYN_9_975—WaveForUs) in the framework of the operational programme “Competitiveness and Entrepreneurship” and Regions in Transition (OPC II, NSRF 2007–2013).

References

Androulidakis YS, Kombiadou KD, Makris CV, Baltikas VN, Krestenitis YN (2015) Storm surges in the Mediterranean sea: variability and trends under future climatic conditions. Dynam Atmos Ocean 71:56–82

Krestenitis YN, Androulidakis Y, Kontos Y, Georgakopoulos G (2010) Coastal inundation in the north-eastern Mediterranean coastal zone due to storm surge events. J Coastal Conserv. doi:10.1007/s11852-010-0090-7

Krestenitis YN, Androulidakis YS, Kombiadou K, Makris C, Baltikas V (2015) Operational forecast system of storm tides in the aegean sea (Greece), 2015. Aquatic sciences meeting, global and regional perspectives—North Meets South, 22–27 February, Granada, Spain

Pytharoulis I, Tegoulias I, Kotsopoulos S, Bampzelis D, Karacostas TS, Katragkou E (2015) Verification of the operational high-resolution WRF forecasts produced by WaveForUs project, 16th WRF users’ workshop, 15–19 June, Boulder, CO, USA

Schwiderski EW (1980) On charting global ocean tides. Rev Geophys 18(1):243–268

Willmott CJ (1981) On the validation of models. Phys Geogr 2(2):184–194