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Hindcast of extreme hydro-meteorological events along the Bulgarian Black Sea coast

Anna Kortcheva, Vasko Galabov, Marieta Dimitrova, Andrey Bogatchev

National Institute of Meteorology and Hydrology, Sofia, Bulgaria

Corresponding author details:
National Institute of Meteorology and Hydrology (NIMH),
66 Tzarigradsko shosse blvd, 1784 Sofia, Bulgaria; e-mail: Anna.Kortcheva@meteo.bg

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INTRODUCTION

High waves and storm surge are linked to severe storms and represent major hazards for the coastlines. Knowledge of the extreme hydrometeorological parametrs during the storms is of significant importance for the sustainable development of a coastal zone. It is rare that there exists a sufficiently long term history of accurate measurements of extreme storm generated winds, waves and storm surges. Simulation of historical storm situations is a key tool in examining potential coastal hazards. Hindcasting is the application of the numerical model to estimate waves and storm surges conditions that occurred in the past. In the absence of measured data covering the whole Bulgarian coastline in old periods, storm surges and waves hindcasts can satisfy the need for historical data**.**
A sophisticated dynamical downscaling procedure has been developed and applied by Meteo-France and the National Institute of Meteorology and Hydrology Bulgarian Academy of Sciences (NIMH) within the EU FP7 project Increasing Resilience trought Earth Observation (IncREO) to reproduce high resolution historical atmospheric fields over the Black Sea area. The European Centre of Medium range Weather Forecast (ECMWF) ERA-Interim and ERA-40 reanalysis of wind at 10m and mean sea level pressure have been downscaled with a higher resolution Numerical Weather Prediction (NWP) model ALADIN to the horizontal and time scales suitable for more precise evaluation of hydrometeorological parameters during the extreme weather events such as coastal storms. The wave and storm-surge regional numerical simulations have been carried out for the ten most severe storms over the Bulgarian coast of the Black Sea from the period 1972-2012. The Earth Observation satellite data plays very important role for the verification of the results and for the calibration of the numerical models. JASON1/2 and ENVISAT satellite altimeter and Metop-A scaterometer derived wind and wave data have been used for the verification study.

METHODOLOGY AND DATA

Selection of historical recent storm events (past 40 years) in the western part of the Black Sea.

Storms in the Black Sea are weather related disasters causing coastal hazards: flooding, erosion and destruction of property along the coast. The investigation of the risk of natural hazards in coastal zones is focused on extreme weather including strong winds, high waves and storm surges.

The Bulgarian coast of the Black Sea covers the entire eastern bound of Bulgaria stretching from the Romanian Black Sea resorts in the north to European Turkey in the south, along 378 km of coastline. The Bulgarian national network of marine coastal observations consists of hydro-meteorological stations situated on the Bulgarian shore of the Black Sea and sea level coastal stations of NIMH and the Bulgarian Cartographic Service. Figure 1 shows the Bulgarian coast of the Black Sea and the location of the coastal hydrometeorological stations.
Historical archives and databases of NIMH and the Bulgarian Cartographic Service provided the initial information about available sea-level and wave observations, which were then carefully analysed and refined with human expertise in order to select the severe storm situations along the Bulgarian coastal zones.The synoptic situations associated with these events accompanied by coastal hazards were also examined. The final dataset includes 10 cases over over Bulgaria within the period 1976 - 2012 corresponding to the most relevant well-documented storm conditions associated with high waves and/or high storm surges over the Bulgarian coast of the Black Sea.

Figure 1: The Bulgarian coast of the Black Sea with locations of hydro-meteorological coastal stations.

HIndcast approach

The analysis of past storm surges and waves local observations has allowed us to elaborate a selection of 10 dates from the recent past with significant waves and/or storm surges over the Bulgarian coasts. The hindcast of an individual historical storm consists of two basic steps. First, the time and space evolution of the surface marine wind at 10 m and mean sea level pressure fields have been specified using the downscaling preocedure. The wind and atmospherical pressure fields are used as an atmospheric forcing for the wind-waves and storm surge numerical simulations, as the second part of the process. Finally the validation studies are carried out in order to assess the skill of storm hindcasts.

Atmospheric forcing

ECMWF reanalyses

The main source of information about historical weather phenomena and processes are the reanalysis performed by the ECMWF. Analyses are carried out of all available historical data (including the EO satellite data) for the given time period. ERA-Interim is the latest global atmospheric reanalysis produced by the ECMWF. It covers the period from 1 January 1979 onwards, and continues to be extended forward in near-real time. ERA-40 is a global atmospheric reanalysis of the 45-year period from 1 September 1957 to 31 August 2002. ERA-Interim and ERA-40 products are publicly available on the ECMWF Data Server. The data from these reanalysis are at every six hours with a spatial resolution of about 125 km for ERA-40 and of about 80 km for ERA-Interim. The ECMWF reanalyses are widely used for many climat applications. However, in this form, due to the coarse spatial resolution, these data is not suitable for more precise evaluation of storm situations that lead to extreme marine and hydrometeorological events such as storm surge and high waves and the related adverse effects. To overcome this problem, a downscaling procedure is necessary for the transition to a finer spatial grid and smaller time intervals.

Downscaled fields of wind at 10m and mean sea level pressure

A sophisticated dynamical downscaling procedure has been developed and applied by Meteo-France and the National Institute of Meteorology and Hydrology - Bulgarian Academy of Sciences (NIMH - BAS) within the project IncREO to reproduce high resolution historical atmospheric fields over the Black Sea area. Reanalysis of the wind at 10m and the mean sea level pressure data sets from the European Centre of Medium range Weather Forecast (ECMWF) ERA-40 and ERA-Interim with a spatial resolution of 125 km and 80 km respectively and a temporal resolution of 6 hours have been dynamically downscaled to the spatial grid resolution of 10 km and 1 hour of temporal resolution using the limited area regional atmospheric model ALADIN. ALADIN (**A**ire **L**imitée **A**daptation dynamique **D**éveloppement **I**nter**N**ational) is a spectral model for regional forecast of meteorological fields and elements. The necessary initial and lateral boundary conditions for running ALADIN were provided by Meteo-France (Bresson et al, 2014). All experiments were performed with the operational application of the model ALADIN based on the cycle 37t1. The downscaling procedure has been applied to the all 10 storm situations. The obtained downscaled high-resolutions meteorological quantities have been used for waves and storm surge numerical simulations.

Wave and storm surge models

WAVEWATCH III wave model

WAVEWATCH III (WW3) is a 3rd generation wave model developed by NOAA/NCEP (*Tolman H.L, 2009)* and based on finite difference solving of the balance equation of the spectral wave action in the approximation of phase averaging. The WW3 wave model computes two-dimensional wave spectra. From the two-dimensional spectra, several parameters are computed, e.g. significant wave height (SWH), peak wave period, mean wave period, peak wave direction and mean wave direction. Calculations are executed on a regular latitude-longitude grid over space, a regular directional grid and a logarithmic frequency grid The frequency grid is specified by 25 terms of a geometric sequence with a scale factor 1.1 and the first frequency 0.042 Hz. The propagation directions are discretized with a 15º step (24 directions) The model covers the Black Sea area with a numerical grid of 40°N to 47°N and 27°E to 42°E and space step of 0.125° in latitude and longitude

SWAN wave model

SWAN (Simulating Waves NearShore) (Booij et al, 1999) wave model has been used for the reconstructions of the waves for the chosen historical storms. The SWAN model is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. SWAN accounts for wave propagation and transitions from deep to shallow water at finite depths by solving the spectral wave action balance equation. This equation includes each source term: wind input, nonlinear interactions, whitecapping, bottom friction and depth induced breaking. The model covers the Black Sea area with a numerical grid of 40°N to 47°N and 27°E to 42°E and mesh size of 0.0333° in latitude and longitude

Wave model input.

1. Bathimetry of the Black Sea
2. Downscaled wind fields over the Black Sea; ERA-Interim, ERA-40 reanalysis.

Wave model output quantities.

1. Significant Wave height (SWH)
2. Mean direction of wave propagation

Storm-surge model

The storm-surge model used by the NIMH is the storm-surge model of Meteo-France adopted for the Black sea area (Daniel et al 2001, Mungov and Daniel 2000). The model is depth-integrated (two dimensional storm-surge model, tides are not considered due to the fact, that for the Black Sea they are with amplitude less than 9 cm). The model grid for the Black Sea is regular with a spatial resolution of two minutes (2'). The model domain is covering the entire Black Sea. The bottom friction coefficient over the shelf is 0.0015 and over the liquid bottom is 0.000015. The wind drag coefficient is according to the Smith and Banke formulation (Mungov et al, 2001). The calculations by the model start several days before the storm with zero initial conditions (zero sea level elevation and currents).

The storm surge model input:

1. Bathymetry of the Black Sea (2' grid resolution, provided by the Military Hydrographic Service of Bulgaria)
2. Downscaled fields of mean sea level pressure; ERA-Interim, ERA-40 reanalysis.
3. Downscaled wind fields; ERA-Interim, ERA-40 reanalysis.

The storm surge model output quantities

1. The coastal profile of the maximum storm surge elevations along the Bulgarian Black Sea coast, time series of sea level elevations.

Hindcasts of ocean waves and storm surges have been performed by using wave models WAVEWATCH III and SWAN and storm surge model of Meteo-France, adopted for the Black Sea area. Comparisons between results obtained with and without downscaling have been carried out.

RESULTS

Waves and storm-surge simulations for the Bulgarian coast of the Black Sea.

The WW3, SWAN wave models and the storm-surge model of Meteo-France were driven by the downscaled meteorological fields and by the ECMWF reanalysis. Examples of simulated storm surges and high wave conditions are presented for the one of most severe storm over the Bulgarian coasline for the last 40 years occurred in February 2012. NIMH runs the wave and storm-surge models two times, first with ERA-Interim wind and atmospheric pressure forcing (coarse spatial grid resolution of about 79 km) and the second time with the downscaled (high resolution) atmospheric forcing with a high spatial resolution of 9 km.The computational domains cover the whole Black Sea area and the western part of the Black sea. The output results from the wave models WW3 and SWAN in terms of significant wave height (SWH) at the peak of the storm in the Black Sea on 8 February 2012 are presented in Figure 2. Figure 3 shows the differences between modelled significant wave height obtained with use the downscaled data versus ERA-Interim atmospheric forcing for the storm situation over the Black Sea on 08 February 2012 at 00 UTC.

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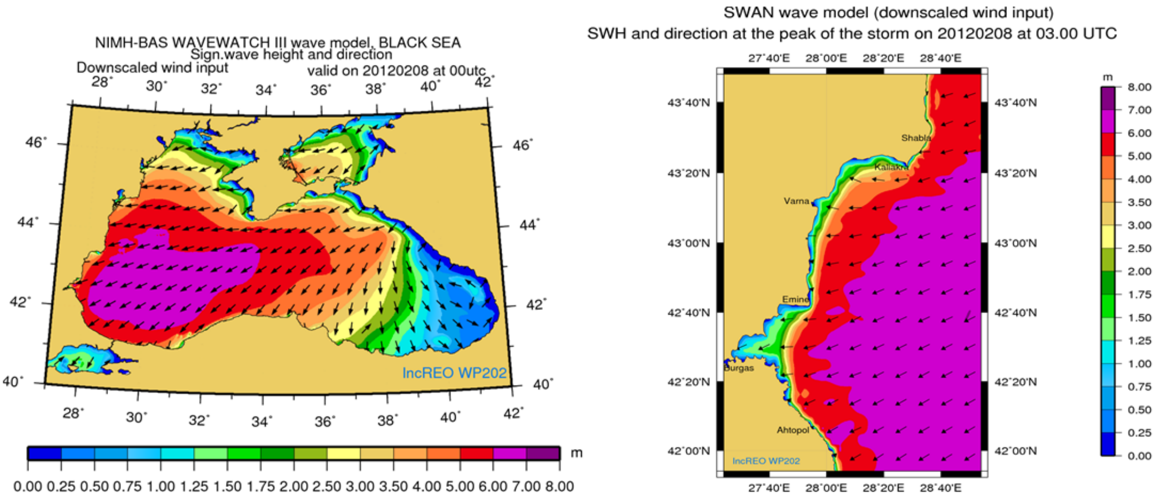


Figure 2: Significant wave heights from the model WW3 with downscaled winds at the peak of the storm in the Black Sea on 8 February 2012 (left) and from the SWAN model (right).

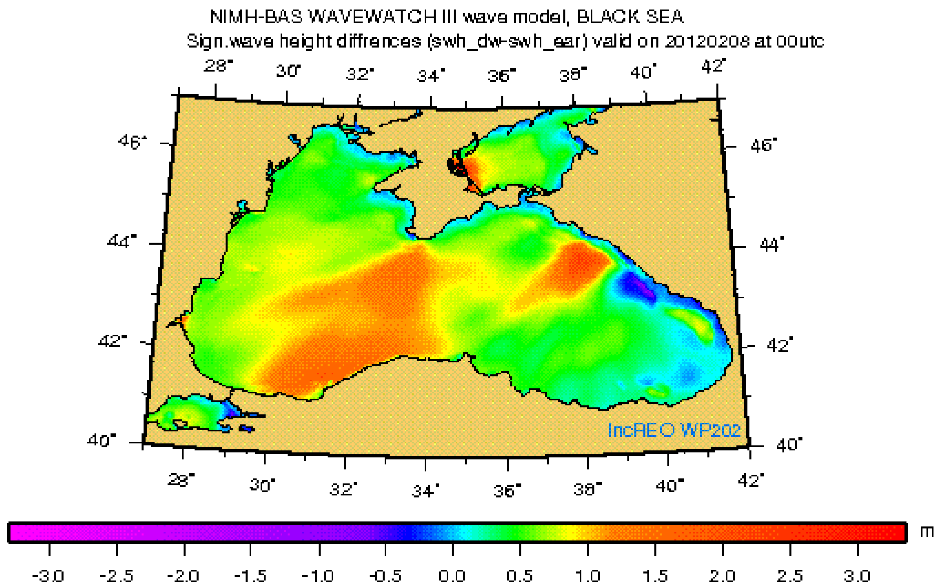


Figure 3: Differences between modelled (WW3) significant wave heigh with downscaled wind and ERA-Interim forcing for the storm situation over the Blac Sea on 08 February 2012 at 00 UTC.

Figure 4 shows the maximum estimated storm-surge water level by the storm-surge model forced by the downscaled ERA-Interim historical reanalyses of 10 m wind and mean sea level pressure along the Bulgarian coast of the Black Sea during the storm in February 2012 (left) and the time series of sea level elevations due to storm-surge near the town of Ahtopol (right).

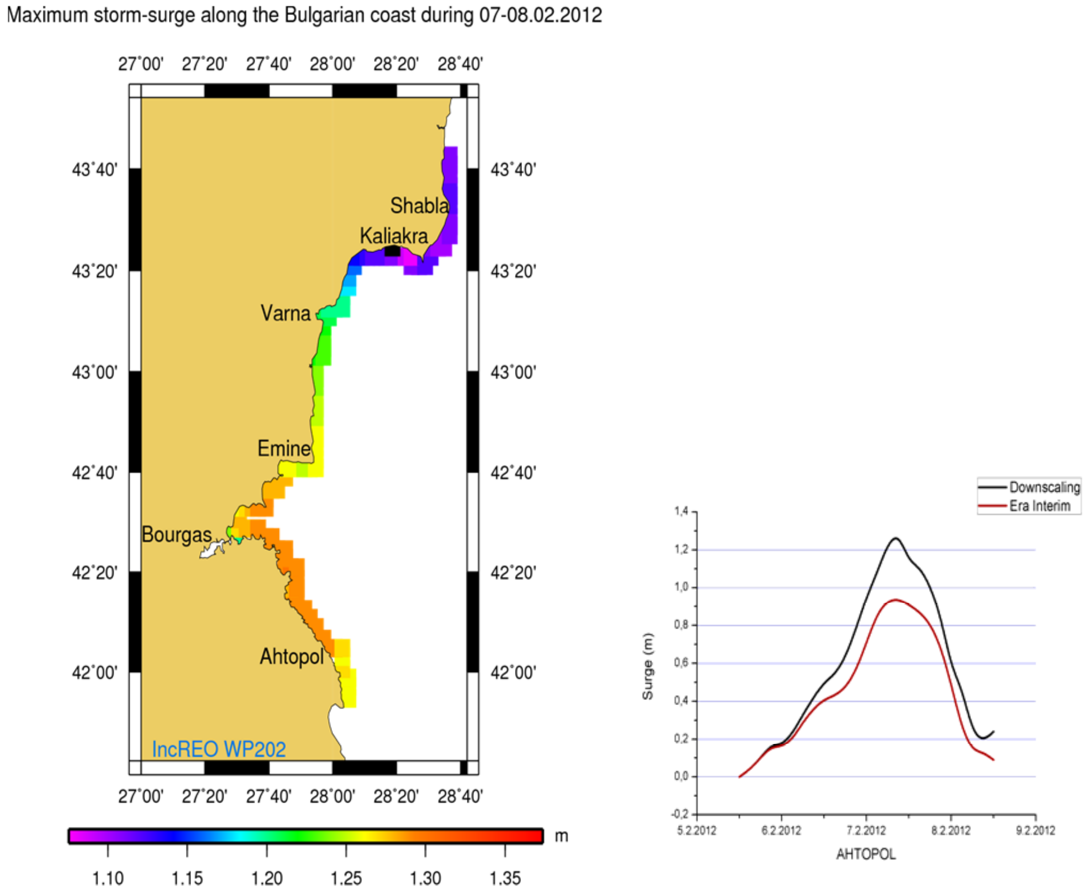
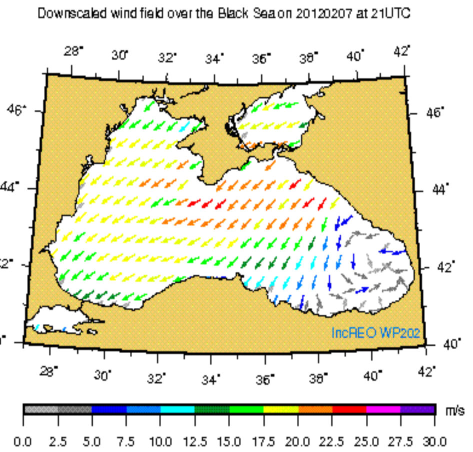


Figure 4: Maximum storm surge along the Bulgarian coast for the storm event during 2012 along the Bulgarian coast of the Black Sea (left) and time series of storm surge at Ahtopol with downscaled (black) and ERA-Interim (red) atmospheric forcing . Source: NIMH.

Validation of results with EO products

The modeled parameters have been validated using all available measurements including the Earth Observation (EO) satellite altimeter and scaterometer data. Downscaled wind fields have been validated using the wind observations from the satellite Metop A (launched in the frame of the joint program of the European Space Agency, EUMETSAT and Centre National d'Etudes Spatiales). Figure 5 presents an example of downscaled wind field (wind speed and direction) over the Black Sea on 07.02.2012 at 21.00 UTC (left) and scatterometer wind data from ASCAT, Metop-A satellite for 07.02.2012 at 18:36 UTC- case BS_201202 (right). Table 1 shows the statistical results from comparison the downscaled wind speed over the Black Sea and scaterometer derived Metop-A satellite data (Galabov et al, 2013). There is a good agreement between the satellite and downscaled wind speed.



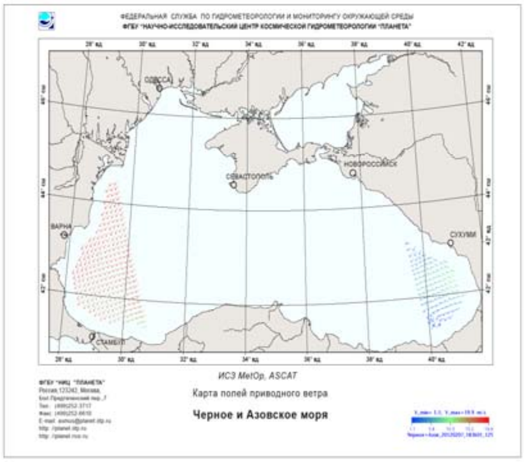


*Figure 5 **:** Downscaled wind field for the storm situation on February 7, 2012 over the Black Sea (left) and scatterometer wind data from ASCAT, Metop-A satellite for 07.02.2012 at 18:36 UTC (right).*

Table 1. Statistical results from comparison the downscaled wind speed and scaterometer data from (ASCAT), Metop-A satellite over the Black Sea for the storm 7-8 February 2012

Date	**Observation mean m/s**	**Model mean m/s**	**Bias m/s**	**RMSE m/s**	**Scatter index**
07.02.2012 18h UTC	16.85	16.82	-0.03	1.04	0.06
08.02.2012 09h UTC	15.72	15.12	-0.60	1.14	0.07
08.02.2012 18h UTC	11.44	11.06	-0.38	1.40	0.12
All observations	13.80	13.38	-0.43	1.26	0.09

Intercomparison studies of Jason1/2 and ENVISAT satellites wave data and modelled results have been carried out for the validation of wave models (Dimitrova et al, 2013, Galabov et al,2013). The results from wave simulations for the storm in February 2012 in the weastern part of the Black Sea are verified using the Envisat *and* Jason-1 radar altimetry (Figure 6).The results from wave simulations are verified separately against the altimeter data from JASON1 and ENVISAT satellites and also for the entire dataset of all satellite altimeter observations during the storm. Table 2 presents statiscs from validation of the SWAN modeled significant wave height (SWH) using two wind inputs: downscaled winds and ERA-Interim wind reanalysis. Taking into account the low bias and scatter index of estimated SWH with downscaled forcing we may conclude that estimations of the highest significant wave heights during the storm of 2012 are more reliable when the simulation were performed using the downscaled wind forcing. SWH obtained from simulations with ERA-Interim forcing is biased with more than 1m below the observed values failing to resemble the extreme character of this storm.

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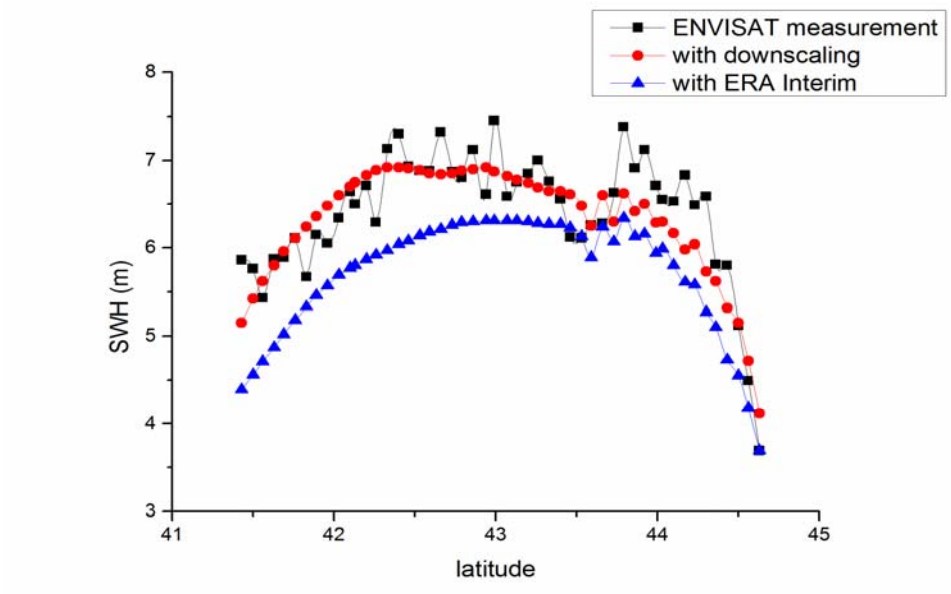

Figure 6: ENVISAT along track values of modelled and altimeter SWH during the storm in the Blak Sea on 8 February 2012.

Table 2 Comparison of SWAN wave model SWH and altimeter along track SWH data from ENVISAT and JASON1 satellites for storm 7-8 February 2012

Satellite track	SWAN type of wind input	Obser vation mean (m)	Model mean (m)	Bias (m)	RMSE (m)	Scatter Index	Number of observatio ns
07.Feb. 08h UTC	downscaled	3.90	4.11	0.21	0.37	**0.10**	44
	ERA_Interim		3.45	-0.43	0.60	0.15	
07.Feb. 14h UTC	downscaled	3.60	3.75	0.15	0.57	**0.16**	76
	ERA_Interim		3.19	-0.41	0.66	0.18	
07.Feb. 20h UTC	downscaled	6.38	6.29	-0.09	0.37	**0.06**	51
	ERA_Interim		5.30	-1.08	1.14	0.18	
08.Feb. 14h UTC	downscaled	5.62	4.68	-0.94	1.16	**0.21**	43
	ERA_Interim		4.40	-1.22	1.37	0.24	
All tracks	downscaled	4.73	4.62	-0.11	0.67	**0.14**	214
	ERA_Interim		3.42	-0.81	0.99	0.21	

Taking into account the low bias and scatter index of the estimated SWH with downscaled forcing we may conclude that estimations of the highest significant wave heights during the storm of 2012 are more reliable when the simulation were performed using the downscaled wind forcing. SWH obtained from simulations with ERA-Interim forcing is biased with more than 1m below the observed values failing to resemble the extreme character of this storm. The storm-surge hindcast was also improved when the high-resolution (downscaled) atmospheric forcing was used for the storm-surge model simulations of historical storm events.

Overall the case of storm in February 2012 is an important example of the advantages of the downscaling approach for the reconstructions of the past severe hydro-meterological conditions. The statistics shows that the use of downscaled forcing improved the results from the numerical simulations of extreme coastal events.

CONCLUSIONS

Numerical wind-waves and storm surge simulation have been used to generate time history of winds, waves and storm-surge heights during the storm situation along the Bulgarian coast of the Black Sea. The resulting data sets of extreme hydro-meteorological parameters represent climatological information on dangerous hydro-meteorological events: strong winds, high waves and storm-surges along the coastal zones of Bulgaria. Such information is especially important in areas where measurements are insufficient or unavailable as is the case along the Bulgarian coast. This information has already been used to calibrate the wave and storm surge numerical models, which are the main part of the multi hazard Early Warning System of NIMH and to improve the Bulgarian version of the official European web-based service of weather warnings METEOALARM.
Hindcasts of ocean waves and storm surges have been performed using wave and storm surge numerical models forced by the downscaled atmospheric fields. The ECMWF ERA-Interim and ERA-40 reanalysis of wind at 10m and sea level pressure have been downscaled with a higher resolution Numerical Weather Prediction (NWP) model ALADIN to the horizontal and time scales relevant to storm surges and waves simulations. The downscaling of the reanalysis of meteorological observations plays a crucial role not only for the correct representation of past events (extreme storms, etc.) but also for the reliability of the models predictions. The spatial resolution plays a very important role to minimize the errors, to correctly represent the topography in the models and is especially important for the successful identification of the vulnerable areas at a regional scale. The modeled parameters have been validated using all available measurements including the Earth Observation (EO) satellite altimeter and scaterometer data. The advantages of the downscaling approach has been demonstrated for the reconstructions of the past severe hydro-meterological conditions. The statistics shows that the use of downscaled forcing improved the results from the numerical simulations of extreme coastal events.
Coastal storm hazards are the result of a complex interplay of wind, water, and local features. The best tools for assessing these hazards are numerical models combined with statistical analysis.
The European project IncREO, Increasing Resilience through Earth Observation, aims at providing tools and solutions to Civil Protection and disaster management to improve preparedness and mitigation planning for areas highly vulnerable to natural disasters. An extreme weather event can involve multiple hazards at the same time or in quick succession. In addition to strong winds and high waves, winter storms can result in storm-surge and flooding. Wave and sea level high-resolution data can help to mitigate the effects of flooding. The obtained results from numerical simulations in combination with statistical analysis can be used for the visualisation of potential flooding areas and damage assesment due to storm surges and wind waves along the Bulgarian coast of the Black Sea (Assman et al, 2014).

ACKNOWLEDGEMENTS

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