STORM SURGES DURING A MEDICANE IN THE IONIAN SEA

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Abstract

Medicane Ianos in September 2020 was one the most severe storms that formed over the Mediterranean Sea with Category 2 Hurricane characteristics. Ianos induced high storm surges along its pathway and led to significant increase of the sea level in the central Ionian Sea, at the Ionian Islands and along the western Greek coasts. We analyzed the characteristics of the storm surges and estimated the coastal inundation levels based on simulations of flooded areas and satellite ocean color images.

Keywords: sea level, Mediterranean Sea, coastal inundation, numerical modeling, remote sensing, Medicane.

1. Introduction

The intense atmospheric cyclones over the Mediterranean Sea with characteristics like tropical cyclones, with windless "eyes", spiral rain-bands, on the order of 300 km in diameter, and surrounding hurricane-force cyclonic winds (up to Category 1 Hurricane on the Saffir-Simpson scale; Emanuel, 2005) are termed as "Medicanes" (Cavicchia et al., 2014). A severe Medicane, named Ianos, with characteristics similar to a Category 2 Hurricane (recorded 1-min average winds of 44.1 m/s), affected central and eastern Mediterranean during 15-20 September 2020 (Lagouvardos *et al.*, 2021; https://marine.copernicus.eu/news/following-cyclone-ianos-across-mediterranean-sea). Ianos Medicane caused severe damages on both inland and coastal areas, especially in central and southwestern Greece, causing extensive flooding, infrastructure destructions and human casualties. The main motivation of this study is to examine the variability of the meteorological effects on the distribution of the induced storm surges and the consequent inundation along coasts of the central Mediterranean during this severe event.

2. Material and Methods

The Sea Level Anomaly (SLA) and circulation characteristics during the Ianos passage over the affected coastal regions are investigated with the use of a 2-D hydrodynamic model for barotropic circulation (High Resolution Storm Surge: HiReSS model) operating in both forecast (Operational System Wave4us; http://wave4us.web.auth.gr/; Krestenitis *et al.*, 2017) and hindcast (Androulidakis *et al.*, 2015) modes. HiReSS simulates the 2-D barotropic mode of the hydrodynamic circulation in large water bodies, enclosed seas, gulfs, and coastal areas over a rather shallow continental shelf, based on the shallow water equations. Atmospheric forcing of the hydrodynamic simulations was derived from operational Advanced Reasearch - Weather Research and Forecasting (WRF-ARW) simulations (Pytharoulis *et al.*, 2015; forecast mode: 15km x 15 km) and from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis products (hindcast mode: 10km x 10km) covering the study period of Ianos (September 2020). The coastal inundation has been estimated with two techniques: 1) the computation of the Normalized Difference Water Index (NDWI; Gao, 1996) derived from Sentinel-2 satellite images before (15/9) and after (20/9) the storm passage, and 2) the Coastal FLOODing (CoastFLOOD) model which is a 2-D horizontal, mass balance, coastal inundation model, based on the concepts of the established LISFLOOD-FP model for coastal (and river) plain flooding. Field measurements of sea elevation were collected by available tide-gauge sensors along the coasts (IOC/UNESCO; https://www.ioc-sealevelmonitoring.org/) to validate the performance of the numerical simulations and estimate the storm surge intensity during Ianos Medicane.

3. Results

3.1. Evaluation of Storm surge simulations

Herein, we extend previous evaluation of the HiReSS model (Krestenitis *et al*., 2011; Androulidakis *et al*., 2015; Makris *et al*., 2021) to test the model's efficiency in simulating the storm surges during the Ianos event. The comparison between the simulated and in situ SLA at 8 coastal stations of the Ionian and Aegean Seas is presented in Table 1. The Pearson correlation coefficients between the hindcast simulated data and observations ranged between 0.62 and 0.86, with smaller Root-Mean-Square-Errors (RMSEs) in comparison to the forecast simulations. Although the usage of ECMWF operational analyses as meteorological forcing of the HiReSS significantly improved the SLA simulations (hindcast mode), the forecasts conducted by the operational system (WRF/ARW-fed HiReSS simulations) provide useful real-time daily predictions that improve in time, as they are forced by daily updated meteorological forecasts. The maximum SLAs were detected for the Ionian Sea coastal areas with the highest at western Peloponnese (e.g., Katakolo).

Table 1. Validation of HiReSS model performance in hindcast and operational forecast modes (left and right columns, respectively) against field observations, during September 2020 at 8 selected stations. SLA and RMSE in m.

	Sites	Hindcast Mode				Forecast Mode			
	STATION	SLA Max	Pearson Correlation	RMSE	Willmott Skill Score	SLA Max	Pearson Correlation	RMSE	Willmott Skill Score
1	Catania	0.13	0.79	0.028	0.80	0.02	0.72	0.047	0.40
2	Gokceada	0.06	0.80	0.026	0.94	0.04	0.70	0.042	0.89
3	Kalamata	0.12	0.63	0.025	0.80	0.10	0.64	0.039	0.65
4	Katakolo	0.29	0.86	0.030	0.90	0.21	0.87	0.028	0.92
5	Kiparisia	0.20	0.62	0.034	0.75	0.16	0.66	0.039	0.76
6	Otranto	0.12	0.73	0.021	0.86	0.04	0.64	0.044	0.50
7	Peiraias	0.12	0.70	0.027	0.83	0.09	0.66	0.041	0.67
8	Thessaloniki	0.08	0.71	0.033	0.91	0.08	0.65	0.049	0.84

The highest SLA (SLA Max_{Obs}=0.27 m; SLA Max_{Model}=0.29 m) were measured in Katakolo (west Peloponnesus; Fig. 1) on 18/09 00:00 UTC (Figure 4a). The core of the Ianos Medicane was over Cephalonia and Zakynthos Islands on 18/9 00:00, with very strong cyclonic winds (>20 m/sec) blowing towards the coast of Peloponnese (Fig. 4b). The onshore wind field led to the accumulation of seawater masses strengthening the storm surges along the western coasts.

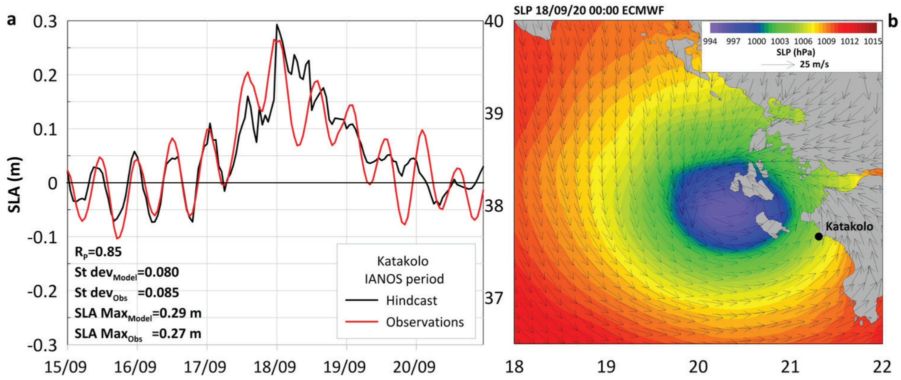

Fig. 1: (a) Variation of SLA derived from the hindcast simulation and the observed data at Katakolo (west Peloponnesus) during the Ianos passage (15/9-20/9) in the Ionian Sea. (b) Map of 2-D horizontal distributions of Sea Level Pressure (SLP) and winds, derived from the ECMWF analysis at the time of maximum SLA (18/9 00:00 UTC).

3.2. Analysis of marine weather conditions

The evolution of the marine cyclone, defined by the 10-cm SLA contour, is shown in Fig. 2. The sea level varied among high values between 17/9 and half of 18/9, when the storm reached the Greek coasts.

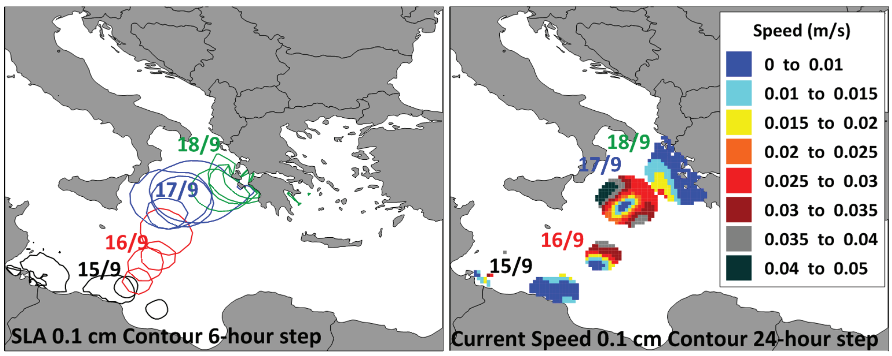

Fig. 2: Evolution of the marine cyclonic eddy (10-cm SLA contour) and distribution of the barotropic current speed from 15/9 to 18/9.

The spatially averaged current velocities inside the eddy revealed the highest values on 17/9. After the storm landfall on 18/9, the extension of the eddy and the respective storm surge signal significantly reduced from 100,000 km^2 to 40,000 km^2, when the SLA values above 10 cm spread along the western coastline of Greece.

3.3. Impacts on the coastal zone

The highest storm surges and the flooding impacts of the Ianos Medicane were mainly detected at the coasts of the central and southern Ionian Sea, especially around Cephalonia Island (0.25-0.30 m; Fig. 3). During the timespan of Ianos event, the inverse barometer effect was very strong over the Ionian Sea and the southwestern Aegean coasts (Pearson correlation coefficient>0.80; Fig. 3b). Although the storm surges over the Ionian Sea are mainly affected by the winds (Krestenitis *et al.*, 2011; Androulidakis *et al.*, 2015), in the case of a Medicane coming from the central Mediterranean, both wind and inverse-barometer contributed on the storm surge formation.

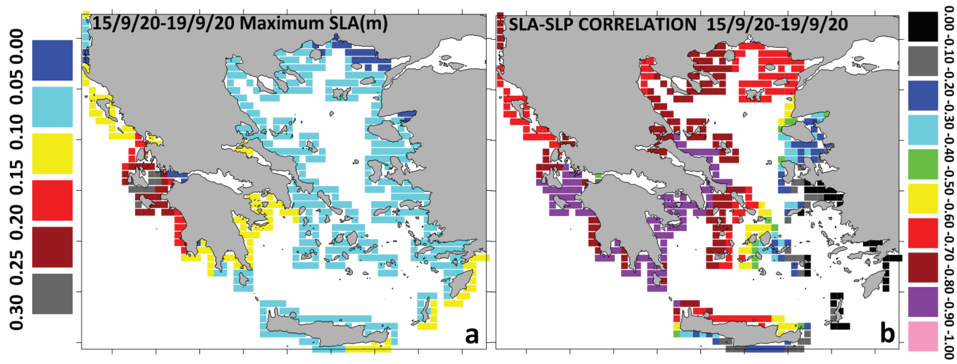

Fig. 3: (a) Maximum SLA and (b) Pearson correlation coefficients between SLA and SLP (ECMWF analysis) at the coastal cells of the Ionian and Aegean Seas during Ianos passage (15/9/20-19/9/20).

Eight coastal regions with extensive areas of land elevation lower than 1 m in the central Ionian Islands have been identified based on very high resolution (dx = 2 m) DEM data of the Hellenic Cadastre service (https://www.ktimatologio.gr/) (Fig. 4a).

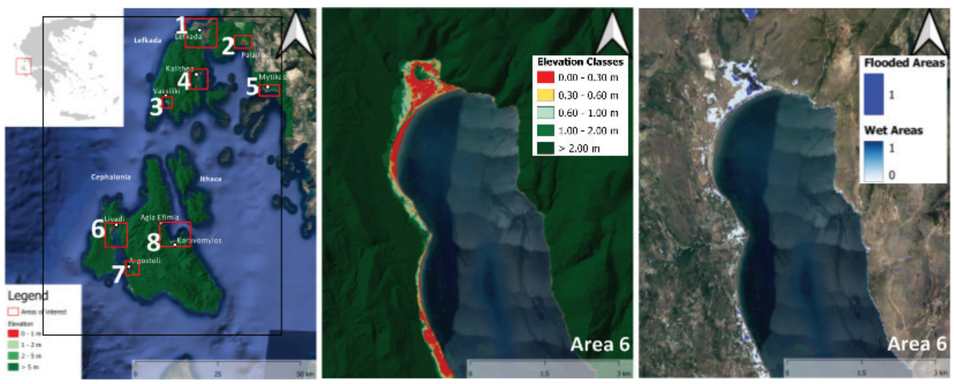

Fig. 4: Land elevation derived from the high-resolution DEM (2m) (a) over the central Ionian Sea and (b) over Area 6. (c) Flooded and Wet Areas derived from the NDWI difference between 15/9 and 20/9 for Area 6.

The largest extent of the coastal zone with land elevation lower than 0.30 m is identified at Area 6 in the Gulf of Argostoli, Cephalonia (Fig. 4b), where the potentially inundated area by a 30 cm sea level rise, is around 0.6 km^2. The mean NDWI difference in Area 6 is highest among the 8 selected coastal regions and is associated to the large number of "wet" cells presented in Fig. 4c (light blue areas). The increased levels of NDWI difference after the storm is a strong indication that the Ianos -induced surge might have boosted the inland moisture levels. A small portion of this area remained flooded ("flooded" cells) on 20/9 (blue areas in Fig. 4c). The area, still covered with water on 20/9, consisted of the 2.7% of the entire lowland (0-0.3 m) coastal zone of Area 6. The SLP dropped below 1000 hPa over the area (Fig. 5a), accompanied by strong surge-favorable southeasterly winds (Fig. 5c). Strong onshore currents accumulated waters inside the gulf of Area 6 in the evening of 17/9 (Fig. 5b), rising the SLA above 20 cm (Fig. 5d). In order to isolate the storm surge contribution on the observed flooding, which may also have other sources (e.g. precipitation, drainage basin runoff), we conducted numerical simulations with CoastFLOOD that used boundary conditions of the realistically simulated SLA (Fig. 5b) at the shoreline. Although, the simulated flooding is weaker than the observed, extensive flooding up to 200 m inland has been confirmed by both techniques (Fig. 5e).

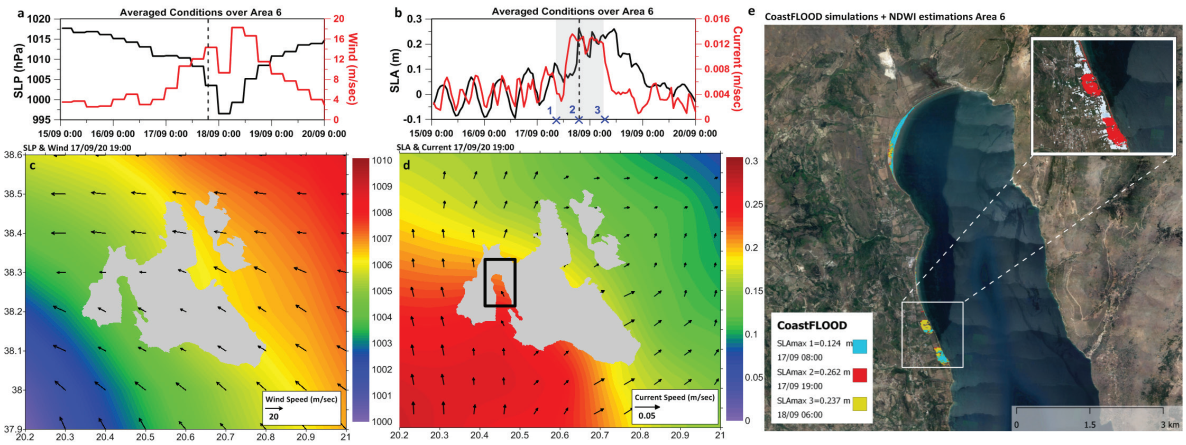

Fig. 5: Evolution of (a) SLP-Winds (ECMWF) and (b) SLA-Currents during 15/9-19/9 period averaged over Area 6. Maps of (c) SLP-Winds and (d) SLA-Currents over Cephalonia Island on 17/9 19:00 UTC. (e) Map of Flooded Areas derived from CoastFLOOD simulations during three characteristic dates (Fig. 4b). Insert in 4e: Estimations of simulated (red) and satellite ("Wet" areas with light blue) over the southwestern coastal region.

4. Conclusions

Ianos Medicane induced significant storm surges along its pathway and increased the sea level over the central Ionian basin, in the Ionian Islands' littorals and along the western Greek coasts. The prolonged stall of the Medicane over the central Ionian on 18/09 induced cyclonic onshore winds and respective currents along the entire coastline increasing the storm surge levels. Several coastal areas of the central Ionian Sea with land elevation lower than 30 cm were flooded during the storm surge. Ocean color images before and after the storm surge event (NDWI technique) in combination with coastal flooding modeling (CoastFLOOD model) provided a reliable estimation about the extension of the inundation.

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