MEDICANES AND ITS METROLOGICAL EFFECTS IN THE MEDITERRANEAN SEA: CASE STUDY OF MEDICANE IANOS

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ABSTRACT: A rising amount of data suggests that human-produced greenhouse gases (GHGs) are altering the Earth's climate. Past metrological events can be used for studying and calibrating the prediction models to predict future extreme events and their effect on coastal flooding due to wave heights and storm surges in the Mediterranean Sea. The paper studies the past and future Medicanes and its metrological effects in the Mediterranean Sea to achieve a sustainable resilient infrastructure perspective in the Mediterranean ports for climate adaptation. DHI MIKE21 SW and HD FM numerical modules are used to study past extreme events of Medicane Ianos and predict future extreme events. This simulation is prepared to study the future and past extreme events of eastern Medicanes, and their effect on oceanographic wave heights and storm surges generated in the Mediterranean Sea. The predicted significant wave height (H_s) within the eastern part of the Mediterranean Sea can reach up to twelve meters, which can cause severe damage to offshore and nearshore infrastructure. The predicted storm surge (S_s) within the eastern part of the Mediterranean Sea reaches 40 centimeters, which can cause coastal flooding, unpredicted wave runup, overtopping and civilian coastal incidents. The result of the analysis shows that performing a regular risk assessment by numerically studying the effect of climate change on extreme atmospheric events for Mediterranean Sea is essential to achieving a sustainable resilient infrastructure perspective for Mediterranean ports. It is recommended to perform a regular risk assessment of the effect of climate change on extreme atmospheric events for the Mediterranean Sea.

1. INTRODUCTION

A rising amount of data suggests that human-produced greenhouse gases (GHGs) are altering the Earth's climate. Climate models may be useful for future changes, but their application is limited because they do not fully reflect the predictability of the present climate. Hence, several approaches have been created to incorporate models of future climate. Currently, it is becoming more crucial for coastal projects to comprehend the possible consequences of climate change. Evaluation of impacts necessitates forecasts of future climate under elevated GHGs **Error! Reference source not found.**.

In previous studies, Han [2] found that mean sea level will continue to rise and likely accelerate, which will increase the likelihood of coastal flooding. Nucera et al. **Error! Reference source not found.** found that the main factors that influence coastal flooding are storm surges, tidal excursions, and run-up. Woodruff et al. **Error! Reference source not found.** suggested in their article that the causes of coastal flooding include accelerated sea level rise and an increased frequency of tropical cyclones. Meanwhile, Pezza and White **Error! Reference source not found.** found that the duration of coastal flooding will increase as sea levels rise. The coastal flooding is caused by climatic factors such as sea level rise and tropical storm surges **Error! Reference source not found.**. Coastal numerical modelling, along with simulating case studies of extreme events, can provide risk mitigation solutions on how coastal flood resilience can be mitigated and expected in the future.
Simulation of hindcast data from past extreme events is a means to assess coastal flooding risks for future Mediterranean Sea extreme events. Mediterranean tropical-like cyclones are known as Medicanes. Simulations of cyclones and Medicanes in the Mediterranean Sea help evaluate the coastal elements against extreme conditions driven by atmospheric extreme events. The impact of climate change on extreme weather events is a key topic of current oceanographical, coastal, and metrological research. To predict future climate extreme events, climate models should capture relevant characteristics of past and present events [7]. Cavicchia et al. **Error! Reference source not found.** indicated that most of Medicanes, as atmospheric extreme events, are generated in the western area of the Mediterranean Sea. However, Medicane Ianos was generated and recorded in the eastern part of the Mediterranean Sea as a shifting likelihood of severe events. Medicanes originate in parts of the Mediterranean region where cold air incursions in the upper troposphere may cause thermal disequilibrium patterns in the atmosphere comparable to those associated with tropical storm development. Medicanes are medium-warm-core cyclones that represent one of the most devastating natural disasters on Earth [10].
The quasi-Mediterranean basin is an ideal location for the formation of cyclonic typhoons. Most of them are cyclones with baroclinic and orographic origins, but sometimes a few low-pressure systems may also develop. Medicanes form and grow over the sea and are associated with strong winds and significant precipitation **Error! Reference source not found.**. Zhang et al. [13] indicated that there is significant variation in Medicane characteristics from year to year, but they identified a total of more than 50 extreme atmospheric events in Medicanes by analyzing the ERA5 dataset from 1979 until 2017. The months of September through March are peak cyclone months. In comparison to tropical cyclones, Medicanes tend to be less powerful. By analyzing a 39-year atmospheric dataset ERA5, Medicanes are responsible for up to 5 percent of all severe rainfall and other extreme oceanographical physical related phenomena, such as coastal extreme waves and storm surges occurrences in numerous places along the Mediterranean Sea. Accurate estimates of extreme atmospheric events, such as Medicanes, along the Mediterranean Sea coasts are critical now and will likely become much more so in the future of coastal and marine projects [14].
Hence, the article aims to study Mediterranean Sea Medicanes and its metrological effects through the study of Medicane Ianos as a case study. The article provides a calibrated

numerical simulation of Medicane Ianos and its effect on Mediterranean Sea storm surges to fulfill the article's objective.

2. MATERIALS AND METHODS

One of the primary methods for assessing the oceanological and coastal risks posed by future extreme events that may occur in the Mediterranean Sea is to simulate data from previous extreme events. The simulation of past extreme events such as cyclones and Medicanes in the Mediterranean Sea aids in evaluating the linked coastal infrastructure against the simulated physical wave heights and storm surges generated by atmospheric extreme events for the European coastlines along the Mediterranean Sea. This helps to minimize long-term uncertainty connected with infrastructure lifespan and substantial environmental consequences. DHI MIKE21 SW and HD FM numerical modelling are constructed with a logical sequence as shown in Figure 1 to study previous extreme events and predict future atmospheric extreme events and oceanographical consequences as a market requirement for achieving the United Nations Sustainable Development Goals (UN SDGs).

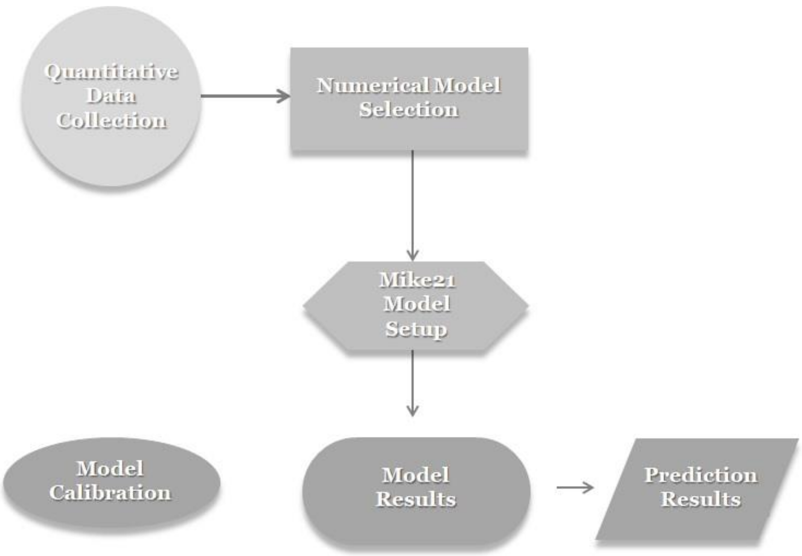

Figure 1: Flow chart for DHI MIKE21 SW and HD FM numerical model construction.

2.1 Quantitative Met-Ocean Data Collection

Medicane Ianos is one of the most potent and lethal Mediterranean Medicanes that have emerged in recent years [16]. The strength of Medicane Ianos' Category 2 was recorded. The Greek Meteorological Service designated Ianos as a medical storm. The cyclone expanded into Medicane Ianos after forming near Libya. Ianos generated intense wind gusts and a substantial storm surge. According to estimations, the system was a tropical cyclone with 65 km/h winds on September 15, 2020. On September 17, 2020, Medicane Ianos began to hit

Europe by affecting the Western Greek islands. On September 21, the remaining fragment of Ianos was able to find its ultimate resting place in the northwest corner of Egypt, near Marsha Matruh. Ianos was also well monitored using low-level characteristics. The vorticity pressure was 850 hPa, and the spiral band occupied the same region [17].

The spiral ring around Medicane Ianos's core is plainly visible and resembles the cloud formations seen in tropical storms. The cloudless spot, known as the Ianos eye, has a minimum diameter and maximum diameter of approximately 50 and 200 kilometers, respectively. The Medicane activity was greatly decreased in a 200-kilometer radius around the Medicane center [18]. The characteristics of ASCAT verified by SMAP and CIMSS ATMS wind data for Medicane Ianos are shown in Table 1 and Figure 2 [**Error! Reference source not found.**,[19][20]].

Table 1. Characteristics for the Medicane Ianos from September 16 to September 21, 2020, with a time step of 6 hours

Date	*Cumulative time steps (Hours)*	*Longitude [°E]*	*Latitude [°N]*	*Radius (km)*	*Wind speed (m/s)*	*Central Pressure [Pascal]*
14-09-20	0.00	16.70	31.20	50	12.9	101300
14-09-20	6.00	16.90	31.80	50	15.4	101200
14-09-20	12.00	16.40	32.20	50	18.0	101100
15-09-20	18.00	15.70	32.90	100	18.0	101000
15-09-20	24.00	15.30	33.30	200	18.0	100900
15-09-20	30.00	15.40	33.10	200	18.0	100700
15-09-20	36.00	15.90	33.70	200	20.6	100400
16-09-20	42.00	16.60	34.20	200	23.2	100100
16-09-20	48.00	16.90	34.40	250	25.7	99700
16-09-20	54.00	17.30	35.60	300	30.9	99200
16-09-20	60.00	17.10	36.70	400	33.4	98800
17-09-20	66.00	17.50	36.90	400	30.9	99000
17-09-20	72.00	18.20	37.00	400	28.3	99100
17-09-20	78.00	18.80	37.60	400	30.9	98900
17-09-20	84.00	19.80	37.80	400	33.4	98600
18-09-20	90.00	20.50	38.00	400	38.6	98200
18-09-20	96.00	20.60	38.40	400	36.0	98900
18-09-20	102.00	20.50	38.50	300	28.3	99700
18-09-20	108.00	21.10	37.90	250	20.6	100000
19-09-20	114.00	21.30	37.40	200	18.0	100200
19-09-20	120.00	21.20	36.40	200	18.0	100200
19-09-20	126.00	22.20	35.40	200	20.6	100000
19-09-20	132.00	23.00	34.70	200	25.7	99700

20-09-20	138.00	23.60	34.10	200	20.6	99900
20-09-20	144.00	24.50	33.50	200	18.0	100200
20-09-20	150.00	25.30	33.10	100	18.0	100400
20-09-20	156.00	25.90	32.50	50	15.4	100600
21-09-20	162.00	26.40	31.80	50	15.4	100700
21-09-20	168.00	27.10	31.50	50	15.4	100800

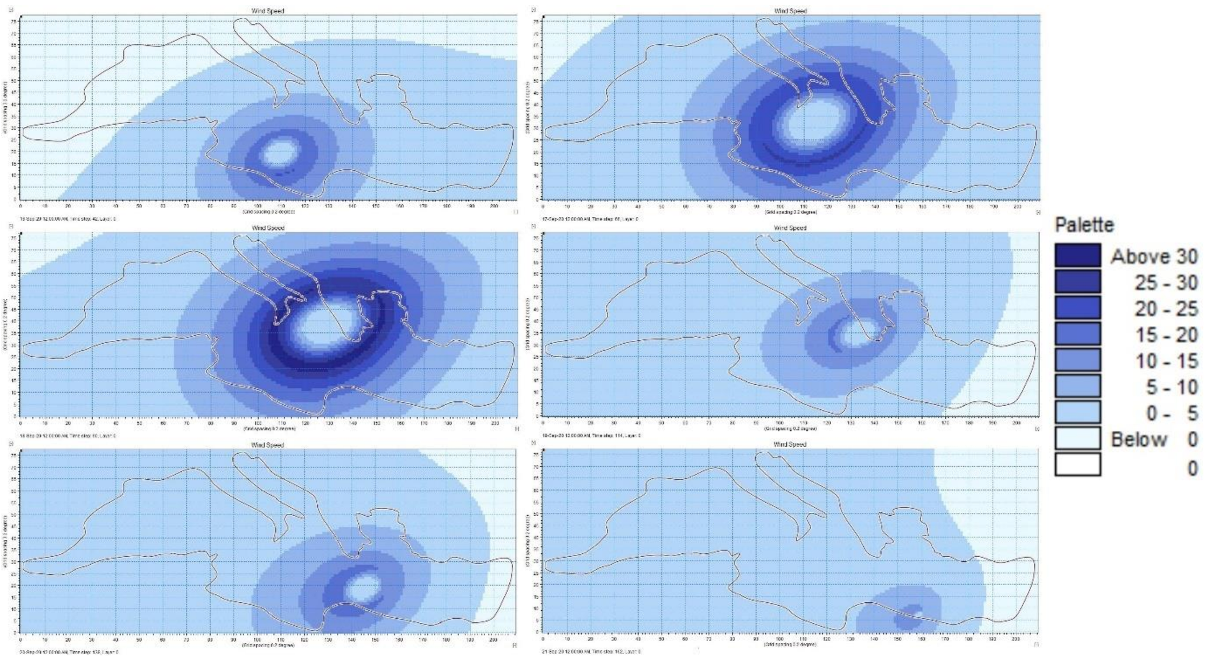

Figure 2: Wind speed during Medicane Ianos from September 16 to September 21, 2020, with a time step of 24 hours.

Cavicchia et al. [9] indicated that most of the Medicanes atmospheric extreme events are generated in the western area of the Mediterranean Sea, as indicated in Figure 3 with more than 90 Medicanes detected in the Mediterranean Sea. However, Medicane Ianos was generated and recorded in the eastern part of the Mediterranean Sea as a shifting likelihood of severe events. To cover the rare Medicanes generated in the eastern area, an assumption for 1% predicted Medicane (1 in 100-year event) is provided in Table 2. This assumption based on past data is selected to study the future and past atmospheric extreme events and their effect on oceanographic wave heights and storm surge generated in the Mediterranean Sea based on a calibrated numerical model of Medicane Ianos. This prediction model is prepared to predict the future of the European Coastlines under a future predicted atmospheric extreme events based on past Medicane-generated events from 1948 to 2011, which is adapted from

Cavicchia et al. **Error! Reference source not found.**, and mimics the pattern of the Medicane Ianos pathway **Error! Reference source not found.**.

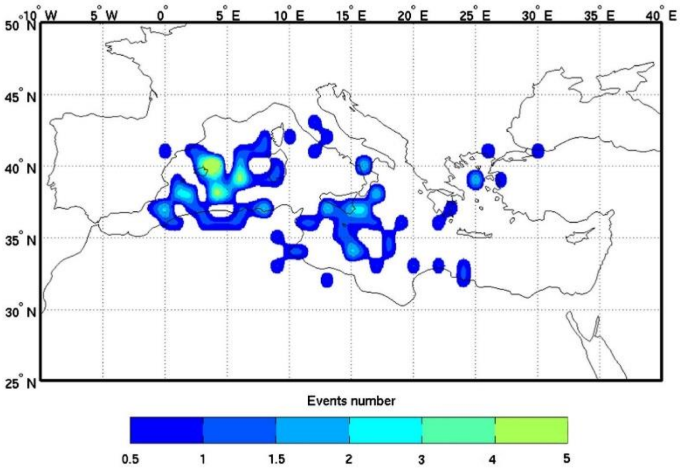

Figure 3: Wind Medicane generated events from 1948 to 2011, adapted from Cavicchia et al. [9].

Table 2. Characteristics for the 1% Predicted Medicane from September 16 to September 21, 2020, with a time step of 12 hours.

Date	*Cumulative time steps (Hours)*	*Longitude [°E]*	*Latitude [°N]*	*Radius (km)*	*Wind speed (m/s)*	*Central Pressure [Pascal]*
14-09-20	0	19.43	30.87	50	12.9	101300
14-09-20	12	19.13	31.87	100	18.0	101100
15-09-20	24	18.03	32.80	200	18.0	100900
15-09-20	36	18.63	33.37	200	20.6	100400
16-09-20	48	19.63	34.07	250	25.7	99700
16-09-20	60	19.83	36.37	400	33.4	98800
17-09-20	72	20.93	36.67	400	28.3	99100
17-09-20	84	22.53	36.47	400	33.4	98600
18-09-20	96	23.63	36.54	400	36.0	98900
18-09-20	108	24.40	35.66	250	36.0	98900
19-09-20	120	25.28	34.75	200	36.0	98900
19-09-20	132	26.19	33.89	200	25.7	99700
20-09-20	144	27.23	33.17	200	29.0	99700
20-09-20	156	28.63	32.17	100	29.0	99700

Quantitative data on the met-ocean shoreline boundaries for the DHI MIKE21 SW and HD FM models are defined in accordance with the Global Self-Consistent, Hierarchical, High-

Resolution Geography Database. The GSHHG database is a high-resolution shoreline database [21]. Figure 4 illustrates the extracted shoreline dataset, which consists of 595 vertices, for the Mediterranean Sea and Southern European Coastlines based on the GSHHG database [22].

The bathymetry data for the numerical modelling is defined in accordance with the GEBCO Database. The GEBCO organization is a non-profit organization that provides publicly available bathymetry. GEBCO organization is sponsored by the Intergovernmental Oceanographic Commission of UNESCO and IHO. The global Seabed-2030 Project was initiated by the United Nations (UN) Ocean Conference in June 2017, and the main goals of the project are strategically aligned with the UN's Sustainable Development Goal, which holds a serial number of 14 for life below water, to preserve and residual sustainable use of the oceans and seas **Error! Reference source not found.**. The extracted bathymetry data for the numerical modelling are 18,349,380 points, as shown in Figure 5 [24].

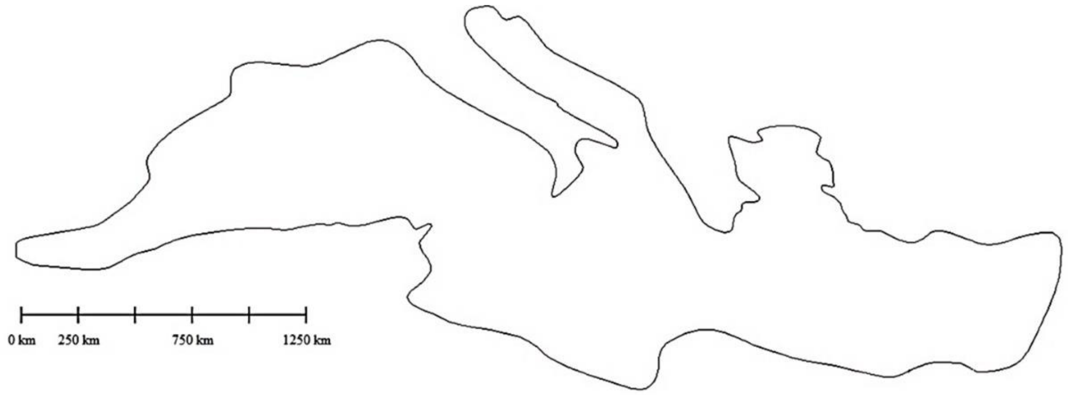

Figure 4: Shoreline for the Mediterranean Sea and southern European Coastline based on GSHHG database.

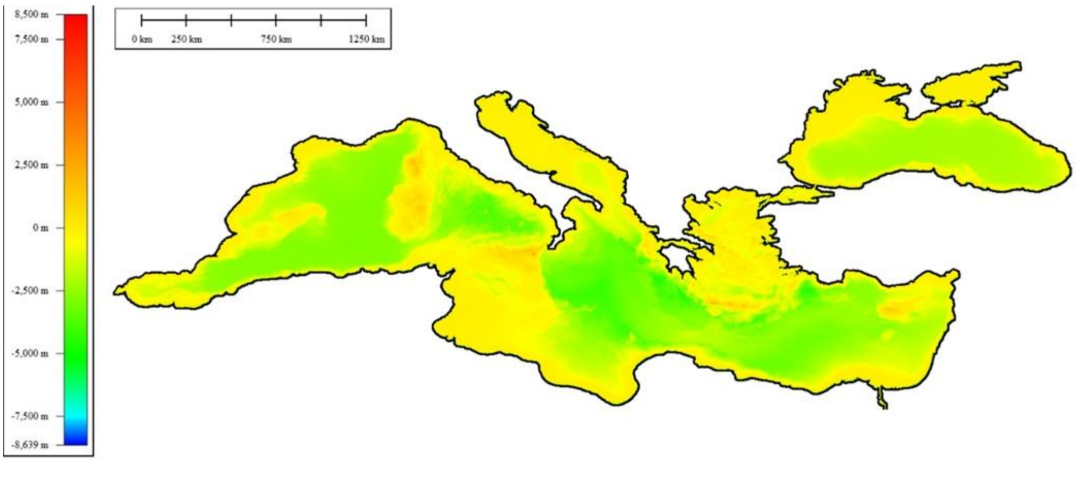

Figure 5: Model's extracted bathymetry data for the numerical modelling based on GEBCO database.

2.2 Quantitative Bathymetric Data Collection and Model Characteristics

When determining design data for marine structures, it is essential to accurately forecast the extreme waves. The security of structures and the likelihood of constructing an economically viable design are based on the reliability of the data. MIKE21 SW FM incorporates spectral wind-wave models made up of meshes that are not uniformly structured. The model simulates the decay and change of wind-generated waves as well as waves in offshore and coastal regions. MIKE21 SW FM is a tool to study wave climatology and oceanography for physical wave heights generated from atmospheric extreme events. It is also used for coastal areas in both hindcast and forward-looking modes. Design of port, offshore and coastal structures is a major area of application. A precise evaluation of the wave load is vital for economical and sustainable design [25].

MIKE21 SW FM's primary purpose is to accurately define and depict wind data. The wind data can be described as changing in space and time for Medicane Ianos. Wave diffraction is taken into consideration for the generated model. Wave diffraction may be utilized in a range of scenarios, such as areas with absorbent or reflective oceans, bays, seas, or coasts for the simulated physical wave heights and storm surges generated from the atmospheric extreme events. Wave radiation stresses and wave heights are used as inputs to the coupled model of MIKE21 HD FM to calculate the storm surge generation from the atmospheric extreme events. The numerical mesh for the models is constructed to ensure that the size of the mesh is suitable for the bathymetry data and that the unstructured mesh size has a stable CFL number as shown in Figure 6. The map projections for the input files are defined as WGS-84 with EPSG 4326. For setting up the mesh for the model, the chart datum is chosen as the Mean Sea Level chart datum (mMSL CD).

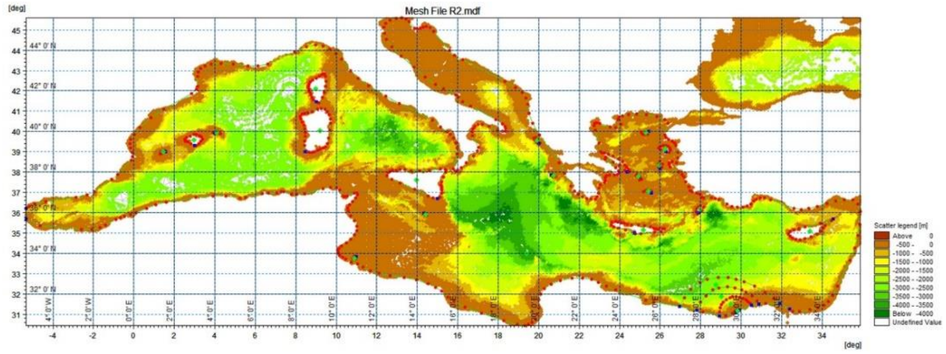

Figure 6: Generated mesh file for the numerical modelling with projection of WGS-84/EPSG 4326

Table 3 illustrates the characteristics and criteria in which DHI MIKE21 SW and HD FM models are built.

Table 3. DHI MIKE21 SW and HD FM models' criteria.

Item	*Setup*
Models Runs	168 Time steps, with intervals of 3600 seconds, and starting on September 14, 2020
Models Type	Spectral Wave Flexible Mesh Model / Hydrodynamic Flexible Mesh Model
CFL Limits	Critical CFL equals 0.95

Wave Breaking	Wave Breaking with specific gamma of 0.8
Bottom Friction	Model of Nikuradse Roughness k_n = 0.04
Bed Resistance	Manning Number equals to 32 (m^(1/3)/s)
Initial Conditions	Spectral JONSWAP fetch Growth Generation with Maximum fetch length of 10000 m
Tidal Conditions	Not included

3. RESULTS AND DISCUSSION

Figure 7 illustrates the resulting oceanographical wave height during Medicane Ianos from September 16 to September 21, 2020, for the deep water, with a time step of 24 hours. The results show a significant wave height (H_s) with a value of approximately 7.0m in the southern coastline area of Italy, the results also show H_s with a value of approximately 12.0m in the western part of Greece during September 17, 2020. However, the H_s value has a minimum significant value of approximately less than 2.0m at the Tyrrhenian Sea. H_s values for Malta's northern area and eastern area have reached a maximum value of approximately 8.2m, the values ranged from 7.1m to 11.3m for the eastern part of Crete, as shown in Figure 8.

Figure 9 illustrates the resulted storm surge (S_s) during Medicane Ianos from September 16 to September 21, 2020, with a time step of 24 hours. The results show a storm surge (S_s) with a value of approximately 0.38m in the southern coastline area of Italy, the results also show S_s with a value of approximately 0.18m in the western part of Greece during September 17, 2020. However, the H_s value has a minimum significant value of approximately less than 0.10m at the Tyrrhenian Sea. S_s values for Malta's southern area and eastern area have reached a maximum value of approximately 0.15m, the values of S_s range from 0.31m to 0.42m for the eastern part of Crete and range from -0.18m to 0.46m for the Aegean Sea.

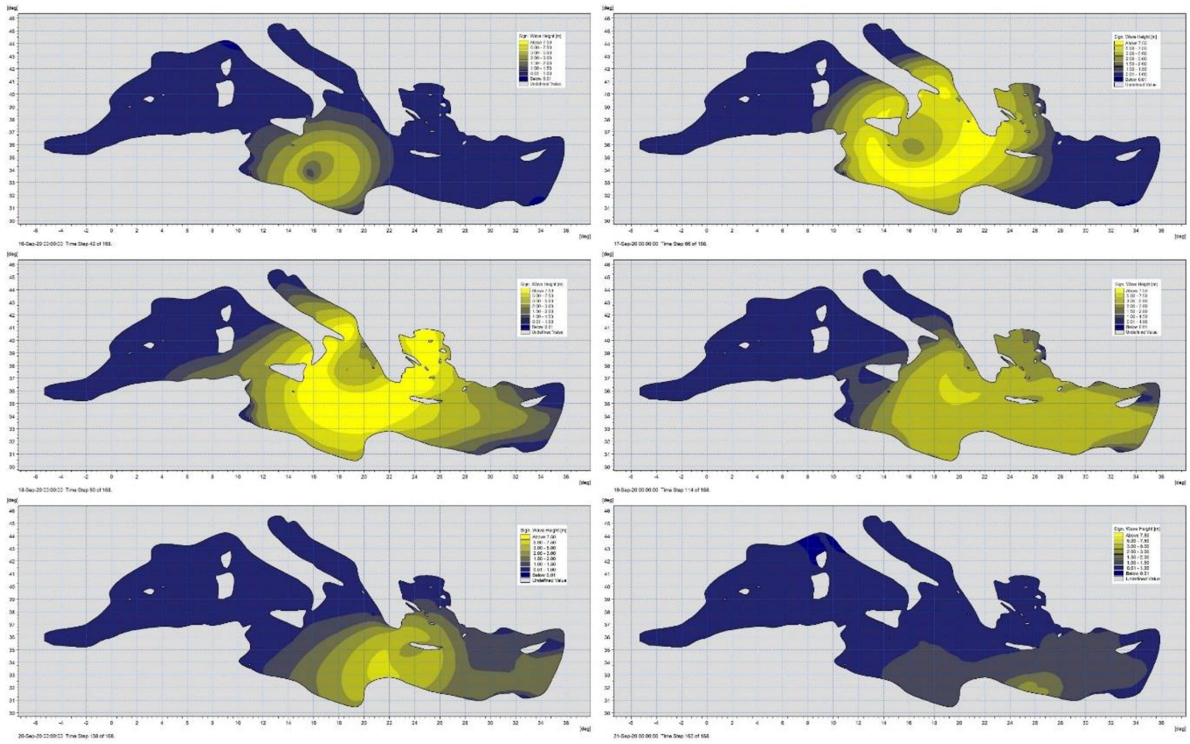

Figure 7: Resulted oceanographical wave height during Medicane Ianos from September 16 to September 21, 2020, with a time step of 24 hours.

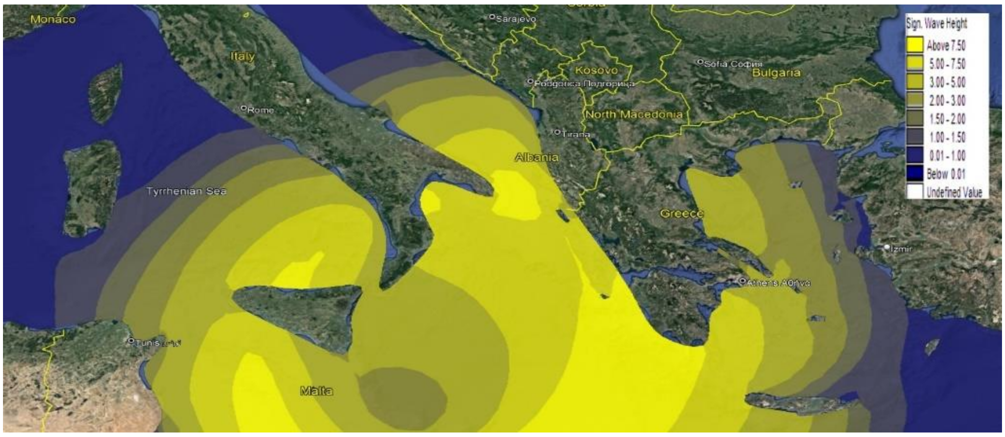

Figure 8: Resulted oceanographical wave height during Medicane Ianos September 17, 2020.

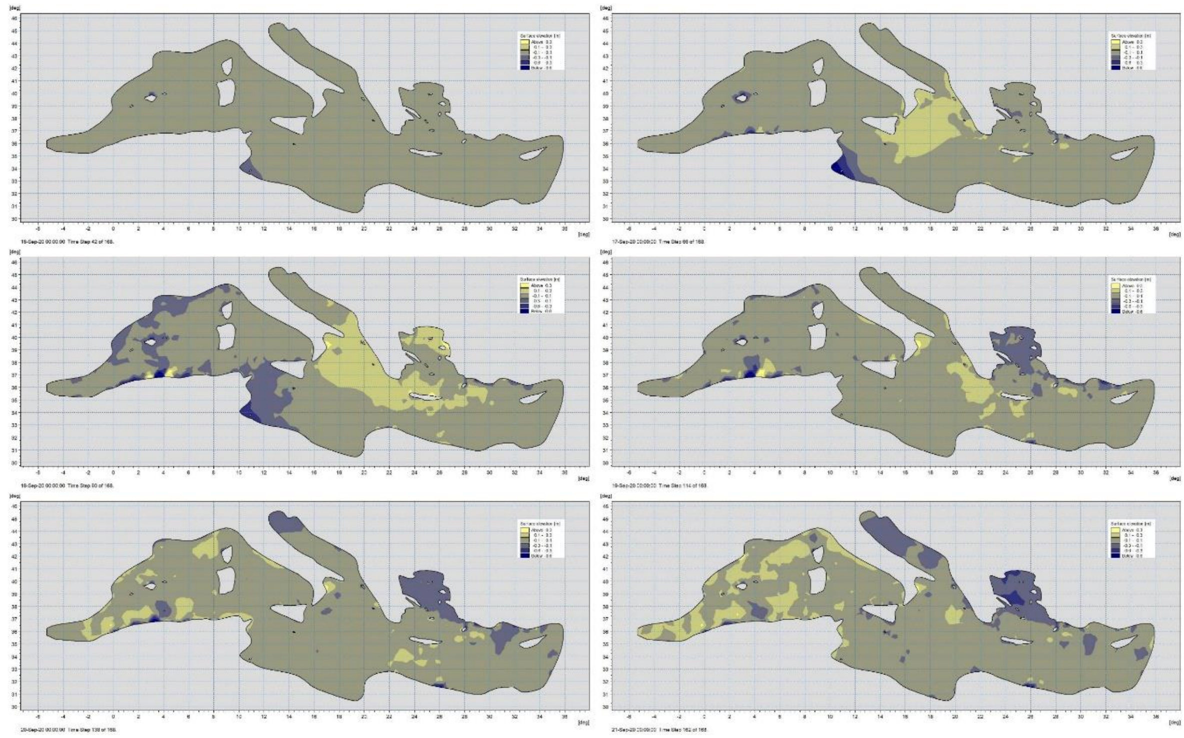

Figure 9: Resulted oceanographical storm surge during Medicane Ianos from September 16 to September 21, 2020, with a time step of 24 hours.

The results of H_s for DHI MIKE21 SW Model are calibrated against the values of H_s for based on Pylos buoy location readings [20], as shown in Table 4 and Figure 10.

Table 4. Characteristics for the 1% Predicted Medicane from September 16 to September 21, 2020, with a time step of 12 hours.

Day/Time [UTC]	*H_s for based on Pylos buoy readings (m)*	*H_s for based on DHI MIKE21 SW Model (m)*
16-09-20	0.61	0.87
17-09-20	3.22	7.39
18-09-20	7.20	7.48
19-09-20	2.95	2.90
20-09-20	1.05	1.31

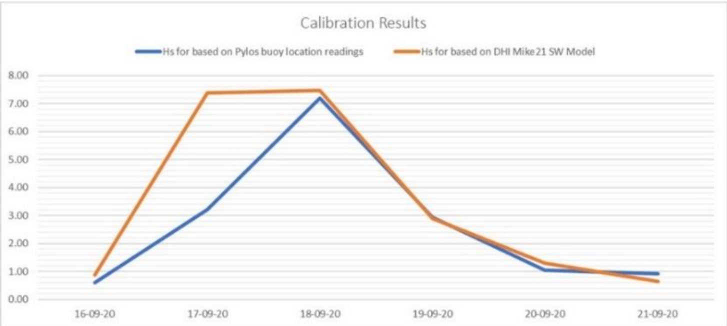

Figure 10: Resulted oceanographical storm surge during Medicane Ianos from September 16 to September 21, 2020, with a time step of 24 hours.

The calibrated model is used to simulate the consequences of 1% predicted Medicane. This simulation is prepared by using the calibrated model, based on the past data of Medicane Ianos, to study the future expected extreme events and their effect on oceanographic wave heights and storm surge generated in the Mediterranean Sea. This prediction simulation model of DHI MIKE21 FM is prepared to predict the future of the Eastern Mediterranean coastlines under a future predicted atmospheric extreme event of 1%, as a future predicted 100-year return period event, Medicane of the eastern part of the Mediterranean Sea.

Figure 11 illustrates the future expected wave height during an expected Medicane similar to Medicane Ianos from September 16 to September 21, for the deep water, with a time step of 24 hours. The results show expected H_s with a value of approximately 7.6m at the southern coastline area of Italy, the results also show H_s with a value of approximately 10.2m at the western part of Greece during September 18. Similar to the results of the calibrated numerical simulation of Medicane Ianos, the H_s value has a minimum significant value of approximately less than 2.0m at the Tyrrhenian Sea. H_s values for Malta's south-eastern and eastern areas have reached a maximum value of approximately 7.6m, the maximum values for the eastern, southern, and western areas of Crete are 8.2m, 11.4m and 11.5m respectively.

Figure 12 illustrates the expected S_s during 100-year return period Medicane from September 16 to September 21, with a time step of 24 hours. The results show future expected S_s with a value of approximately 0.42m at the southern coastline area of Italy, the results also show future expected S_s with a value of approximately 0.41m at the western part of Greece during

September 17. The future expected S_s values for Malta's southern area and western area have reached a maximum value of approximately 0.08m, the values of the future expected S_s for the eastern, southern, and western areas of Crete are 0.52m, 0.43m and 0.22m respectively. In addition, the future expected S_s values range from -0.35m to 0.48m for the Aegean Sea.
To conclude the results and discussions, accurate estimates of wind characterizations and extreme atmospheric events are essential. This is related not just to the quick change in climate and the associated rise in severe storms, but also to the change in the community itself and its new demands for attaining sustainable and resilient infrastructure against future-predicted conditions based on the analysis of past extreme atmospheric events such as Medicane Ianos. Medicane Ianos was recorded in the eastern part of the Mediterranean Sea as a shifting likelihood of severe events. Predicted H_s within the eastern part of the Mediterranean Sea reaches 12 meters, which can cause severe damage to offshore and nearshore civil infrastructures. Predicted S_s within the eastern part of the Mediterranean Sea reaches 0.4 meters, which can cause coastal flooding and civilian coastal incidents. It is recommended to perform a regular risk assessment of the effect of climate change on extreme atmospheric events in the Mediterranean Sea to achieve the European and Mediterranean Sustainability Portfolio's goals. Cyclones simulations and flood risk assessments can support sustainable resilient infrastructure solutions in ports and logistics for climate adaptation as a modern coastal protection measure system [15][27].

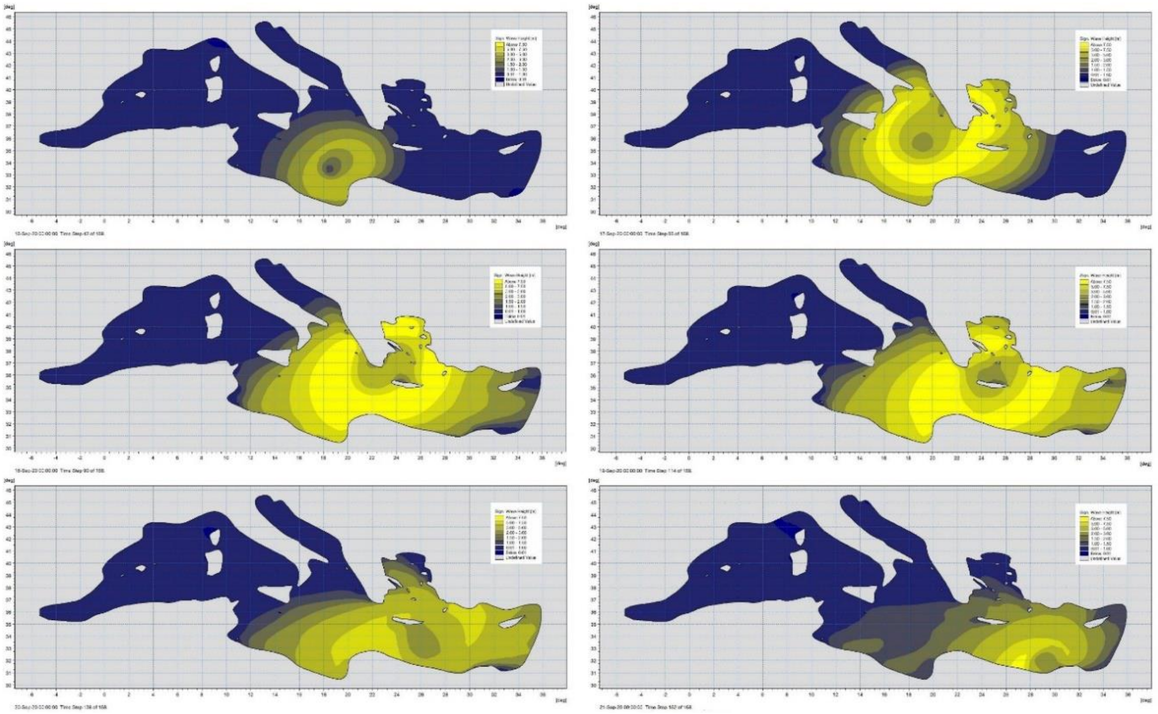

Figure 11: Resulted expected oceanographical wave height during 100-year return period Medicane from September 16 to September 21, with a time step of 24 hours.

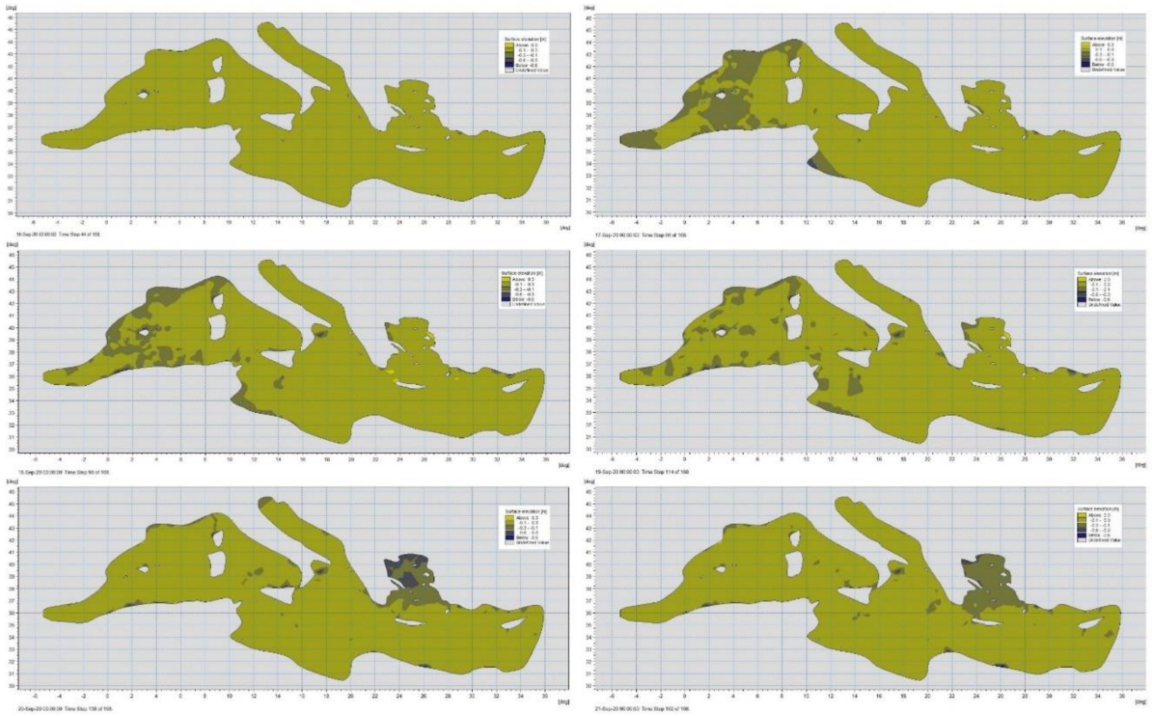

Figure 12: Resulted expected oceanographical storm surge during 100-year return period Medicane from September 16 to September 21, with a time step of 24 hours.

4. CONCLUSIONS

A rising amount of data suggests that human-produced greenhouse gases (GHGs) are altering the Earth's climate. Impact assessment requires climate forecasts under elevated GHGs. Simulations of past extreme events are used to assess oceanological and coastal threats from future Mediterranean Sea extreme events. The impact of climate change on extreme weather events is a key topic of current coastal and metrological research. The most atmospheric extreme events are formed in the western Mediterranean Sea, whereas Medicane Ianos was generated and recorded in the eastern Mediterranean Sea as a shifting likelihood of severe occurrences. Accurate wind characterizations and extreme weather phenomena like Medicanes in the Mediterranean Sea and European coasts are crucial now and will likely become more so in the future of coastal and marine projects. This is due to the rapid climate change and increase in severe storms, as well as the community's growing needs for sustainable and resilient infrastructure against future-predicted conditions based on prior catastrophic climatic events like Medicane Ianos. Hence, the paper simulates Medicane Ianos, an atmospheric extreme event, and its Mediterranean Sea storm surge effects. DHI MIKE21 SW and HD FM numerical modules are used with a logical sequence of data gathering, model setup, and calibration to validate model results to study past extreme events and predict future atmospheric extreme events' oceanographical consequences as a market requirement for achieving UN SDGs.

To conclude the results and discussions, predicted H_s within the eastern part of the Mediterranean Sea reaches 12.0 meters, which can cause severe damage to offshore and nearshore civil infrastructure. Predicted S_s within the eastern part of the Mediterranean Sea reaches 0.4 meters, which can cause coastal flooding, unpredicted wave runup, overtopping and civilian coastal incidents. It is recommended to perform a regular risk assessment of the effect of climate change on extreme atmospheric events in the Mediterranean Sea.

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