Exploring the Signature of the Apollo Medicane in the Central Mediterranean Sea Through Multi-source Data Analysis: Satellites, Radar HF, Marine Buoys, and Seismic Data in October 2021

Luca Piroddi[1(✉)], Adam Gauci[1], Rami Kalfouni[1], Matthew R. Agius[1], Davide Melfi[2], Alfio Marco Borzì[3], Andrea Cannata[3,4], Flavio Cannavò[4], Vittorio Minio[3], Arianna Orasi[5], Salvatore Aronica[6], Giuseppe Ciraolo[7], and Sebastiano D'Amico[1]

[1] Department of Geosciences, University of Malta, Msida, Malta
Lucapiroddi@yahoo.it, sebastiano.damico@um.edu.mt
[2] Italian Air Force Meteorological Service - CNMCA, Rome, Italy
[3] Dipartimento di Scienze Biologiche, Geologiche ed Ambientali - Sezione di Scienze della Terra, Università degli Studi di Catania, Catania, Italy
[4] Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Catania, Osservatorio Etneo, Catania, Italy
[5] Centro Nazionale per la Caratterizzazione Ambientale e la Protezione della Fascia Costiera, la Climatologia Marina e l'Oceanografa Operativa, Italian National Institute for Environmental Protection and Research, Rome, Italy
[6] Consiglio Nazionale delle Ricerche, Via del Mare, 3 Torretta Granitola, 91021 Fraz. Campobello di Mazara, Tp, Italy
[7] University of Palermo, Palermo, Italy

Abstract. In the last decades, the frequency of extreme weather and marine events has drastically increased. During the last week of October 2021 an intense Mediterranean hurricane (Medicane), named Apollo, affected many countries on the Mediterranean coasts. Eight people died as a consequence of the floodings from the cyclone in the countries of Tunisia, Algeria, Malta, and Italy. A preliminary search for possible signatures of the Apollo Medicane by meteorological satellite, radar HF, marine buoy, and seismic data is performed. This was done in a framework of an international collaboration between Italian and Maltese partners for the monitoring of the sea state in scenarios of climate change. The experimental results confirm, at this preliminary stage, the possibility and the usefulness of jointly looking at such phenomena with multiple aims of retrieving a more robust characterization, having a backup alternative in case a primary monitoring network gets failure, and pathing the way to heuristic and data-driven analytical and predictive approaches to Medicanes issues.

Keywords: Apollo Medicane · Seismic Noise · Marine Buoy

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1 Introduction

1.1 Apollo Medicane

In past decades, due to climate change, the frequency of extreme weather and marine events has increased significantly [1]. During the last week of October 2021 an intense Mediterranean hurricane (Medicane), named Apollo by a consortium of European meteorological services, affected many countries on the Mediterranean coasts. The deaths toll peaked up to 8 people, due to flooding from the cyclone in the countries of Tunisia, Algeria, Malta, and Italy [2]. The Apollo Medicane persisted over such areas for about one week (24 October–30 October 2021, Fig. 1) and produced very intense rainfall phenomena and widespread flash flood and flood episodes, especially over eastern Sicily on 25–26 October 2021 [2].

A Medicane can manifest different characteristics at the different stages of its life cycle. It typically starts with features of extra-tropical cyclones that are frequently observed in the middle latitudes, but under certain conditions, it can evolve into phenomena like hurricanes that develop in the tropical belts of the Atlantic, Pacific, and Indian oceans [3]. It is generally triggered by a strong temperature difference between the upper layers of the atmosphere (colder) and those low and close to the earth's surface (warmer) [3, 4]. Evolution into a tropical-like cyclone occurs when there is enough exchange of heat and moisture between the sea and the lower atmosphere, that fuels the development of massive storm clouds [3, 4]. Typical characteristics of mature events are nearly circular symmetry, a deep warm core, a closed eye in its center with spiral cloud coverage around it, and maximum 10 m s^{-1} wind speed at 20–30 km from its center [3].

A recent study examines the interplay between the Apollo atmospheric cyclone and a cyclonic gyre located in the western Ionian Sea [5]. During the event, the temperature in the core of the cold gyre dropped dramatically. The resulting biogeochemical impacts included an increase in oxygen solubility, chlorophyll concentration, productivity at the surface, and decreases in the subsurface layer [5]. Their analysis demonstrated how a coordinated, multi-platform observing system integrated to an operational model in the Mediterranean Sea, dedicated to monitoring ocean and atmospheric parameters would be beneficial to improve our knowledge of the complex processes that may be linked to the Medicanes intensification, their impacts and/or to other extreme events [5].

1.2 Damages Caused by Apollo - Impacts of Apollo Medicane

The storm in study was named as Medicane Apollo on October 28th when it was located in the Ionian Sea, offshore Sicily. This low-pressure system was isolated near the Balearic Islands around the 22nd of October and then moved on the Central Mediterranean Sea producing self-regenerating thunderstorms in Catania on the 24th of October [7]. Figure 2 displays the track of the cyclone along its most intense life cycle. During the tropical phase of Apollo at least 8 people were killed by the storm in Sicily, Malta, Algeria and Tunisia. The highest wind gusts were measured on October 29th (104 km/h) and the pressure minimum value was estimated to 999 hPa [7]. From the convective precipitations associated with Apollo, the Sicilian Meteorological service SIAS measured > 200 mm rain around Syracuse on the same date [7]. Apollo weakened on 30th October 2021

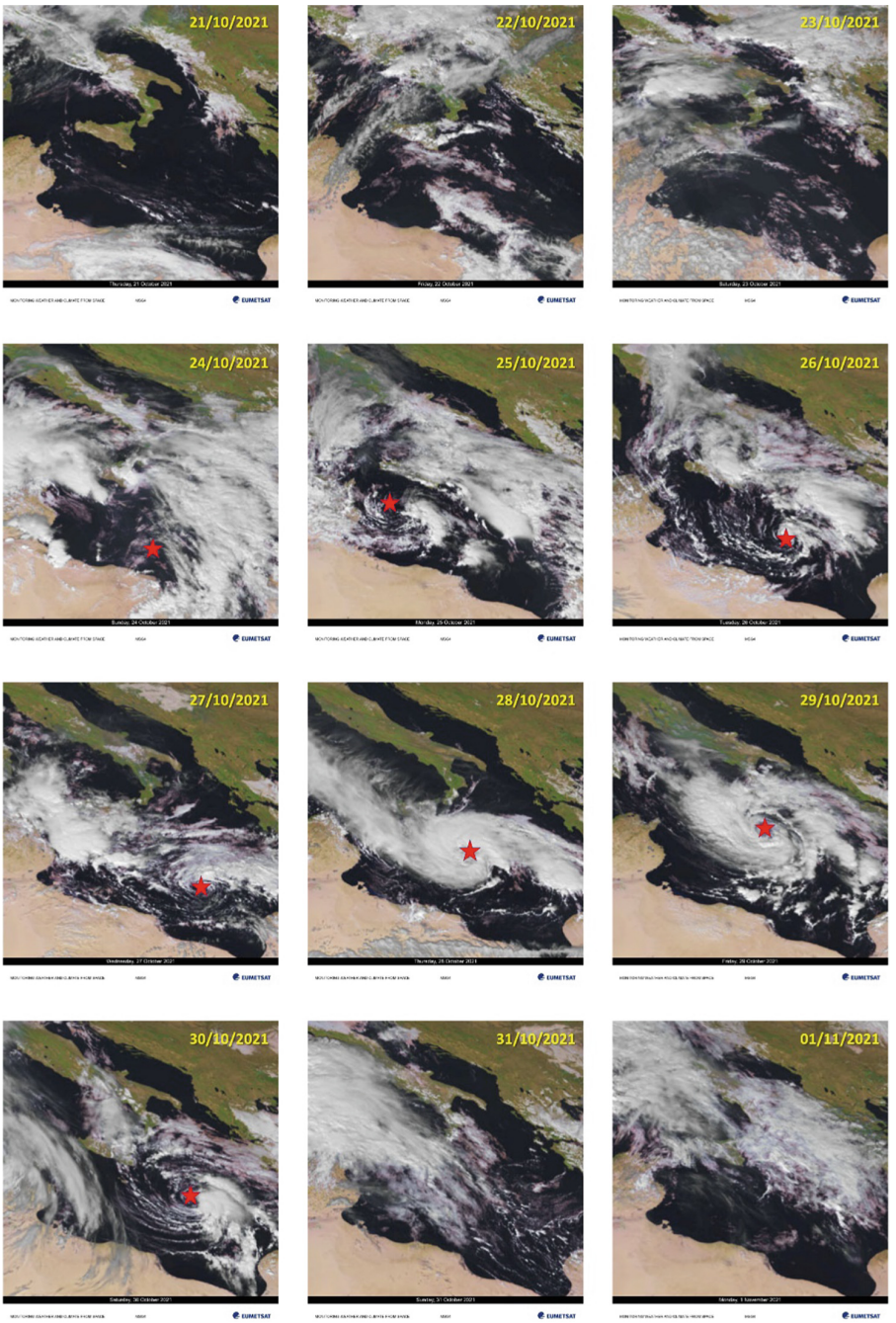


Fig. 1. Tracking of the eye of the cyclone over the RGB Natural Colour Enhanced product from Eumetsat [6] across the Central Mediterranean.

landfalling near Bayda and stayed inland until emerging over the Mediterranean a few hours later. Then, on 2nd of November, it dissipated off the coast of Turkey [7].

More than 100 properties were flooded in Algeria, following heavy rains which started on 23 October [8, 9]. Algiers, Boumerdes, Chlef and Tizi Ouzou were some of the worst hit provinces. Algiers city received more than 140 mm of rain in 24 h from 23–24 October [8, 9]. In Ain Benian, 246 mm of rain was reported, which is more than five times the average rainfall for October (13, MKWeather, 2021). Two fatalities were reported in south-west Algiers, where dozens of people were rescued following heavy rains [8, 10].

Heavy rainfall in Tunisia from 23–24 October produced a reported 168 mm in Ras Jebel and 136 mm in Sidi Thabet in the north of the country [8, 9]. Three fatalities were recorded in Tunisia. In Thala, northwest Tunisia, two fatalities were reported, whilst another fatality was reported in Borj Chakir, near the capital Tunis [8, 11].

Eastern Sicily experienced the highest levels of rainfall, with a total of 520 mm reported at Linguaglossa, Catania, from 24–26 October [8, 12]. On 24 October, heavy downpours produced more than 300 mm of rain near Catania, which is nearly half the average annual rainfall for the island [8, 9, 13]. Two fatalities were reported in Catania region on 24 October and a third one on 26 October [8, 14, 15].

In Calabria, 440.2 mm of rainfall was reported in Fabrizia, which is more than 4 times the monthly average for October [8, 16]. Rainfall totals exceeding 300 mm were also reported at Mongiana, Chiaravalle Centrale, Antonimina and Canolo Nuova in the Calabria region [8].



Fig. 2. Tracking of the eye of the storm during its most intense life cycle.

2 The i-waveNET Framework

Extreme events cause significant impacts on exposed territories, and it is expected that they may have even greater impacts in next future, especially on coastal areas. Consequently, the level of risk associated with sea storms must be continuously monitored and characterized with a view to implementing increasingly targeted and effective mitigation actions [17]. The i-waveNET project, in which this research is conducted, is carried out by Sicilian and Maltese partners and sets up an integrated monitoring system based on numerous synergistic technologies (Fig. 3), consisting of HF radars, marine buoys, seismic stations, weather stations, and tide indicators [17].

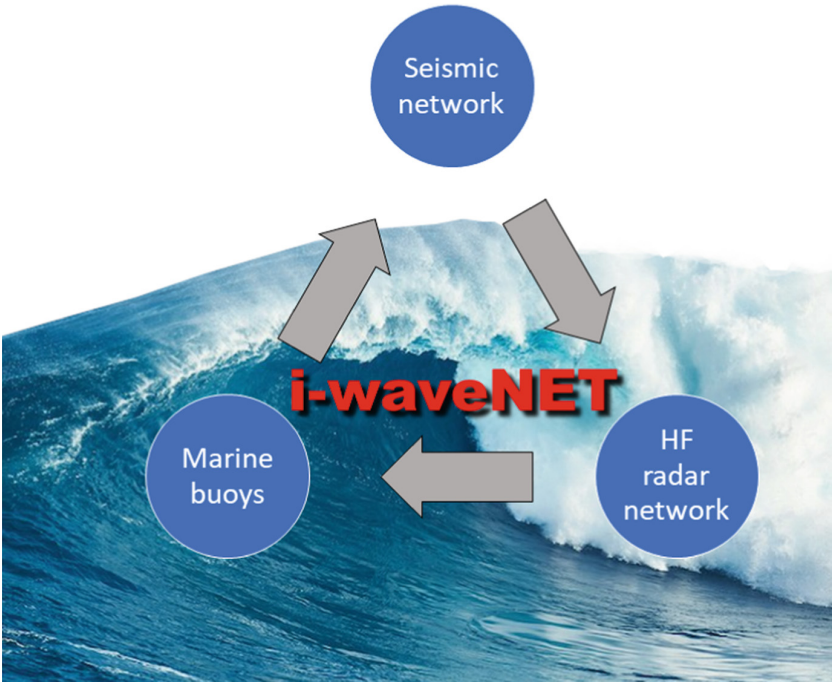


Fig. 3. Sketch of the synergistic marine monitoring networks in the context of the i-waveNET collaborative project.

In the Malta-Sicily Channel, several monitoring systems were already deployed, and this monitoring infrastructure is reinforced and integrates the available technologies by means of i-waveNET.

New weather stations and a new HF radar in strategic points are a first expansion of the operational networks. The permanent seismic networks – managed by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Seismic Monitoring and Research Group, within the Department of Geosciences, University of Malta [18, 19] – is strengthened through the installation of new sensors close the HF radar sites. All these data will be harmonized and analyzed to ensure integration with meteo-marine data.

In the context of the i-waveNET project machine learning algorithms to characterize the sea state through microseism data are implemented. The forcing of a spectral wave model with data also flowing from the monitoring network ensures a real-time sea state monitoring at a regular spatial-temporal grid over a larger domain [17].

Finally, these instrumental networks, integrated with numerical models, supply the input data to a Decision Support System (DSS) in a GIS environment, capable of producing information in line with the conventions of the various stakeholders involved and to influence regional planning activities. Consequently, the i-waveNET project will result in a homogeneous and continuous dataset of measured data, the creation of a dataset on the state of the sea modelled on a regular grid and finally a real-time monitoring system of the physical state of the sea [17].

The main i-waveNET goal is to establish the means to continually mitigate risks due to extreme catastrophic events from the sea. Another example of the environmental effects that even a mid-to-strong sea storm can have on the exposed coasts is given by the collapse of the Azure Window in March 2017 (Fig. 4). The Azure Window was the popular name given to a spectacular, internationally known, natural rock arch that stood on the northwestern coast of the island of Gozo, the second largest island of the Maltese archipelago [20]. Natural coastal arches are usually formed in headlands in which a window is carved mainly through marine action. After years of rapid erosion, on 8 March 2017 the Azure Window collapsed into the sea, leaving no trace above the waterline as an effect of a marine storm with wave heights of 3 m.

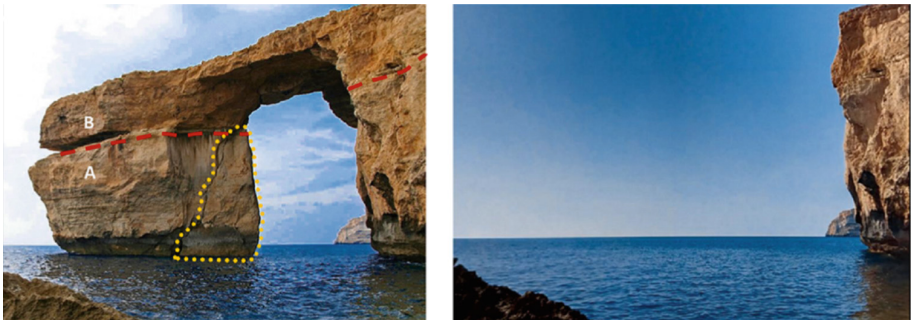


Fig. 4. Azure Window, Gozo: The arch before the collapse (left panel), and a photograph taken from the same point after the collapse (right panel). The boundary between the upper (B) and lower (A) geological stratigraphy is marked with a dashed line. The area highlighted with dots is a block that detached in 2012. After [20]

3 Experimental Datasets

This paper provides a preliminary analysis of the integrated monitoring datasets, looking at the possible qualitative detection of signatures of the Apollo Medicane phases on the experimental datasets. In Fig. 5, the locations of three different kinds of sensors are shown: the three-component seismic station WDD, a digital broadband seismometer

located south of Malta in Wied Dalam [19]; the two-components HF radar sensor SOPU, and the marine wave-buoy SOPU, co-located in Sopu, east coast of Gozo.



Fig. 5. Localization of the environmental monitoring stations: the three-component seismic station WDD, a digital broadband seismometer located south of Malta in Wied Dalam; the two-component HF radar sensor SOPU, and the marine wave-buoy SOPU, co-located in Sopu, east coast of Gozo

3.1 Wave Buoy vs HF Radar

As a first attempt to detect possible signatures of the Apollo Medicane, in Fig. 6, a graphical comparison of wave buoy and radar data for the site of SOPU during the period from 21 October to 2 November is shown. The buoy data are strongly influenced by the drifting of the sensor progressively out of the national waters for the strong winds and wave movements, that happened on 23 October at the beginning of the cyclone not yet a medicane. Nevertheless, in this event the two time-series of wave amplitude show a common behavior with a background wave height of about half a meter and a progressive increase to two meters on 23 October, just before the buoy started drifting. Until the 2 November (last day in the plot) the sea conditions at the two sensors remained quite similar indicating that the buoy had not yet reached positions too far from the observational ring of the HF radar (6 km distance for the plotted data).

Another important result of the HF radar monitoring is the strong correlation between the waves directionality (orange dots in Fig. 6.a) and the position of the eye of Apollo

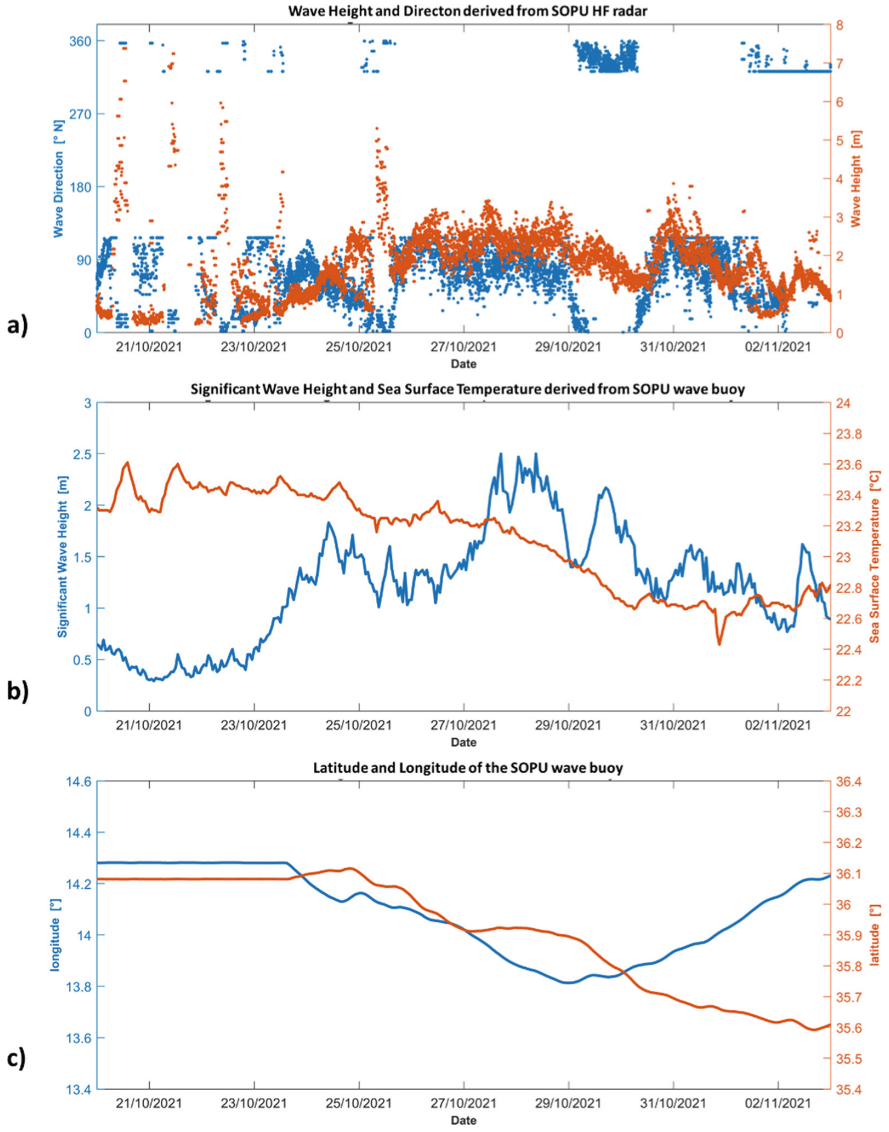


Fig. 6. Graphical comparison of HF radar and buoy data for the site of SOPU. In the top panel, the radar data are plotted for the dates from 21 October to 2 November (a): in orange the wave height in meters, while in blue the related angles of the velocity vector. In the middle panel (b), the buoy data are plotted, indicating in blue the wave height and in orange the sea temperature. In the bottom panel, the two geographical coordinates of the buoy are plotted, showing on 23 October the beginning of the buoy movement out of place which, in the dates out of our graph, lead the buoy to the North African sea. (Color figure online)

(Fig. 2.a). In fact, it is possible to observe the trends to about $-15°/345° \pm 20°$ on the days of 25 and 29 October, when the location of the center of the Apollo perturbation was at its most northern and closest position to Malta.

3.2 Wave Buoy vs Seismic Noise

In the framework of the i-waveNET project, the relation between seismic noise and the state of the sea has been and is being investigated [21, 22].

Borzì *et al.* [21] propose the monitoring extreme meteo-marine events in the Mediterranean area using the microseism, in particular the Apollo Medicane. They investigated the microseism accompanying this extreme Mediterranean weather event, and its relationship with the sea state retrieved from hindcast maps and wave buoys. The spectral and amplitude analyses of the seismic data showed the space–time variation of the microseism amplitude. In addition, they tracked the position of Apollo during the time using two different methods: (i) a grid search method; (ii) an array analysis, obtaining a good match between the real position of Apollo and the location constraint by both seismic methods.

Kalfouni *et al.* [22] derive insights into the state of the sea from seismic noise in the wake of the i-waveNET project. There, the measured wave height at marine buoys is correlated with the vertical component of the seismic noise velocity measured at the seismic monitoring stations with appropriately long time-series. Figure 7 shows a

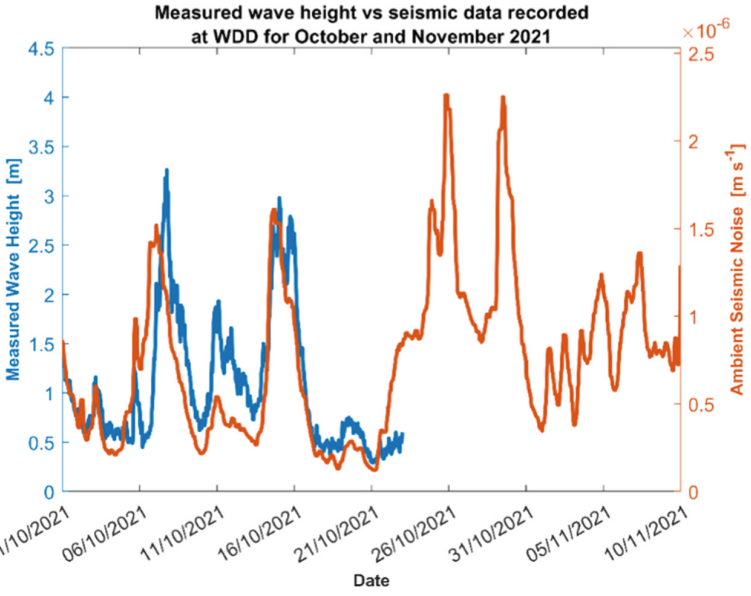


Fig. 7. Graphical overlay of the vertical component of the ambient seismic noise at the WDD station in Wied Dalam (orange plot) and the measured wave height by the SOPU buoy in Gozo (blue plot), until it abandoned the original measuring location. Notice the good correlation between the two datasets. (Color figure online)

graphical overlay of the sea wave height measured at SOPU buoy until it started drifting due to the early phases of Apollo storm (blue) versus the ambient noise velocity at WDD station. Even with this short time period it is possible to notice the strong correlation between the two datasets, and, on the basis of the robust relation obtained on the long datasets, in Fig. 8 the sea wave height at the original SOPU position is reconstructed from the seismological monitoring data using a linear regression model.

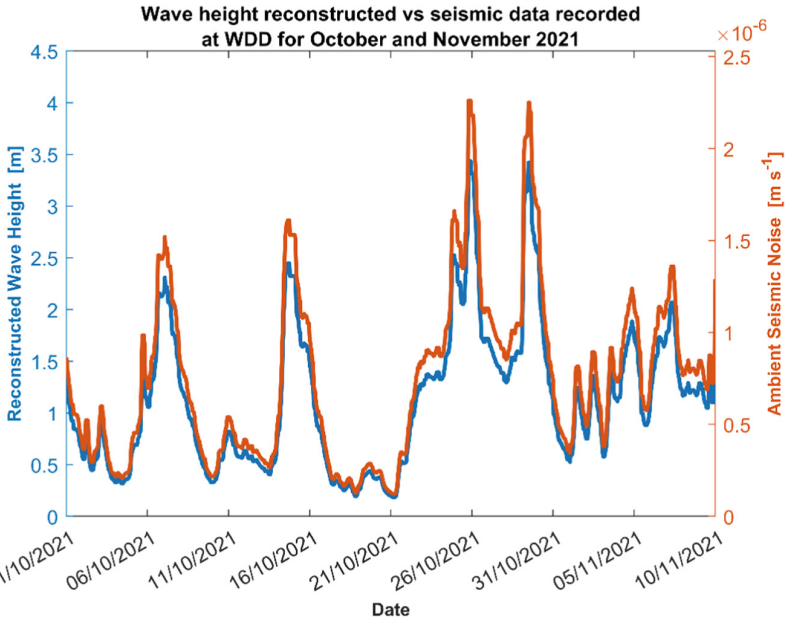


Fig. 8. Graphical overlay of the vertical component of the ambient seismic noise at the WDD station in Wied Dalam (orange plot) and the estimated sea wave height reconstructed using the same dataset. (Color figure online)

3.3 Satellite Data

Geostationary satellite multispectral data are becoming an important tool for monitoring many environmental risks [23–28]. This is particularly true for the study and forecast of strong meteorological events [29–31] in which the thermal infrared bands are extremely useful.

In Fig. 9, a time series of the European HRV-RGB (E-view) for the Apollo case study is presented. The E-View product is an RGB (Red, Green, Blue) composite based upon data from the SEVIRI instrument. It is dedicated to detailed cloud monitoring of the European region and is based on data from the SEVIRI High Resolution Visible (panchromatic) channel combined with data from the IR10.8 channel that provides the temperature information (blue component) [32]. This RGB type concentrates on high cloud monitoring. Thin and thick high clouds have good color contrasts with each other,

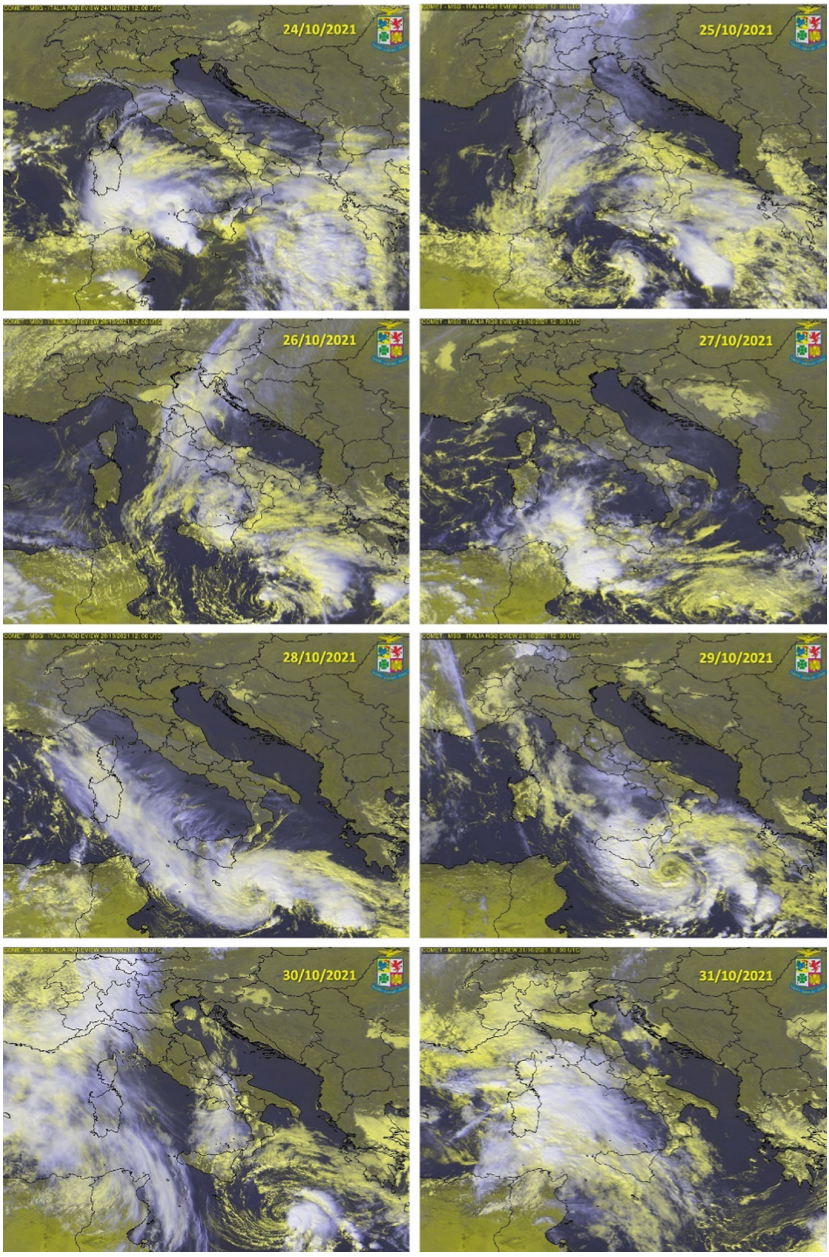


Fig. 9. European HRV-RGB (E-view) for the Apollo Medicane. The white-blue tones indicate the high, coldest and thickest clouds, representative of the mature phases of the storm. (Color figure online)

from lower-level clouds, and from cloud-free regions (including snow/ice) [31]. Intense (and/or long-lived) overshooting tops, gravity waves, long-lived cold U/V and cold rings are indicators of strong updrafts and possibly severity [32].

4 Concluding Remarks

In this paper a preliminary search for a signature of the Apollo Medicane by satellite, radar HF, marine buoy, and seismic data is performed. This is done in a framework of an international collaboration between Italian and Maltese partners for the monitoring of the sea state in scenarios of climate change.

The experimental results here presented, together with the collateral research already published and in the phase of publication, confirm the possibility and the usefulness of jointly looking at such phenomena with multiple aims of retrieving a more robust characterization. This allows to have a backup alternative in case a primary monitoring network gets failure, and to path the way to heuristic and data-driven analyses and monitoring techniques.

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References

1. Swain, D.L., Singh, D., Touma, D., Diffenbaugh, N.S.: Attributing extreme events to climate change: a new frontier in a warming world. One Earth **2**(6), 522–527 (2020)
2. EUMEeTrain, https://eumetrain.org/resources/complete-meteo-hydrological-chain-support-early-warning-systems-weather-scenarios-flooded. Accessed 20 Mar 2023
3. Lagasio, M., et al.: A Complete meteo/hydro/hydraulic chain application to support early warning and monitoring systems: the Apollo Medicane use case. Remote Sens. **14**(24), 6348 (2022)
4. Emanuel, K.: Genesis and maintenance of "Mediterranean hurricanes." Adv. Geosci. **2**, 217–220 (2005)
5. Menna, M., et al.: A case study of impacts of an extreme weather system on the Mediterranean Sea circulation features: Medicane Apollo (2021). Sci. Rep. **13**(1), 3870 (2023)
6. https://pics.eumetsat.int/viewer/index.html
7. https://xaida.eu/medicane-apollo/
8. https://www.jbarisk.com/products-services/event-response/medicane-apollo/
9. https://floodlist.com/africa/algeria-tunisia-italy-medicane-floods-october-2021
10. https://themaghrebtimes.com/floods-in-algeria-the-toll-is-growing/
11. https://www.sott.net/article/459914-Three-killed-in-Tunisia-flash-floods?utm_source=rss&utm_medium=MINT+Social&utm_campaign=RSS
12. https://www.severe-weather.eu/europe-weather/medicane-tropical-cyclone-sicily-italy-malta-flooding-mediterranean-mk/
13. Levantesi, S.: Assessing Italy's Climate risk, Nature Italy. https://doi.org/10.1038/d43978-021-00136-0

14. https://www.bbc.co.uk/news/world-europe-59048809
15. http://www.nimbus.it/eventi/2021/211031TempestaApolloSicilia.htm
16. https://www.worldweatheronline.com/fabrizia-weather-averages/calabria/it.aspx
17. Aronica, S., et al.: The i-waveNet project and the integrated sea wave measurements in the Mediterranean sea. In: 2022 IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea), pp. 484–487. IEEE, October 2022
18. Ferretti, R., et al.: Analysis of the development mechanisms of a large-hail storm event, on the Adriatic Sea using an atmosphere-ocean coupled model (COAWST) (No. EGU22–12876). Copernicus Meetings (2022)
19. Galea, P., Agius, M.R., Bozionelos, G., D'Amico, S., Farrugia, D.: A first national seismic network for the Maltese Islands—the Malta seismic network. Seismol. Res. Lett. **92**, 1817–1831 (2021). https://doi.org/10.1785/0220200387
20. Galea, P., Bozionelos, G., D'Amico, S., Drago, A., Colica, E.: Seismic signature of the Azure window collapse, Gozo, central Mediterranean. Seismol. Res. Lett. **89**(3), 1108–1117 (2018)
21. Borzì, A.M., et al.: Monitoring extreme meteo-marine events in the Mediterranean area using the microseism (Medicane Apollo case study). Sci. Rep. **12**(1), 21363 (2022)
22. Kalfouni, R., Agius, M.R., D'Amico, S., Gauci, A., Galea, P.: Deriving insights into the state of the sea from seismic noise in the wake of the i-WaveNET project. Appl. Sci. (2023, in prep.)
23. Jones, S., Hally, B., Reinke, K., Wickramasinghe, C., Wallace, L., Engel, C.: Next generation fire detection from geostationary satellites. In: IGARSS 2018–2018 IEEE International Geoscience and Remote Sensing Symposium, pp. 5465–5468. IEEE, July 2018
24. Vu, B.N., Bi, J., Wang, W., Huff, A., Kondragunta, S., Liu, Y.: Application of geostationary satellite and high-resolution meteorology data in estimating hourly PM2. 5 levels during the Camp Fire episode in California. Remote Sens. Environ. **271**, 112890 (2022)
25. Liew, S.C.: Detecting active fires with himawari-8 geostationary satellite data. In: IGARSS 2019–2019 IEEE International Geoscience and Remote Sensing Symposium, pp. 9984–9987. IEEE, July 2019
26. Piroddi, L., Ranieri, G.: Night thermal gradient: a new potential tool for earthquake precursors studies. An application to the seismic area of L'Aquila (central Italy). IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. **5**(1), 307–312 (2011)
27. Piroddi, L., Ranieri, G., Freund, F., Trogu, A.: Geology, tectonics and topography underlined by L'Aquila earthquake TIR precursors. Geophys. J. Int. **197**(3), 1532–1536 (2014)
28. Piroddi, L.: From high temporal resolution to synthetically enhanced radiometric resolution: insights from Night Thermal Gradient results. Eur. Phys. J. Spec. Top. **230**(1), 111–132 (2021). https://doi.org/10.1140/epjst/e2020-000247-x
29. McNally, T., Bonavita, M., Thépaut, J.N.: The role of satellite data in the forecasting of Hurricane Sandy. Mon. Weather Rev. **142**(2), 634–646 (2014)
30. Knapp, K.R., Kossin, J.P.: New global tropical cyclone data set from ISCCP B1 geostationary satellite observations. J. Appl. Remote Sens. **1**(1), 013505 (2007)
31. Ciardullo, G., Primavera, L., Ferrucci, F., Lepreti, F., Carbone, V.: New investigation of a tropical cyclone: observational and turbulence analysis for the Faraji hurricane. Remote Sens. **15**(5), 1383 (2023)
32. https://data.eumetsat.int/product-navigator/product/EO:EUM:DAT:MSG:EVIEW