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USE OF THE WRF MODEL TO FORECAST THE EXTREME WEATHER EVENT OF OCTOBER 2021 IN SICILY

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ABSTRACT. In recent decades, the effects of climate change and, in particular those caused by global warming, have been increasingly correlated with weather trends. In fact, recent studies have shown that extreme weather events today occur with greater intensity and frequency than in the past. This is discussed in the most recent IPCC AR6 reports. The southern Mediterranean area is increasingly affected by intense meteorological events, such as for example heavy rainfall and heat waves. In recent years (2020 and 2021), two Tropical-Like Cyclone, also defined as Mediterranean Hurricanes – Medicanes, developed in this area. With this regard, the aim of this work is to study through a modelling approach the so-called Apollo Medicane, which affected the Mediterranean Sea in the last days of October 2021. The extreme weather event caused intense rainfall and strong winds in southern Italy,particularly in eastern Sicily. In this context, the simulation was carried out by using the Weather Research and Forecasting (WRF) model in a configuration at 3 km of horizontal resolution, which was specifically optimized for the Sicily region. Finally, the rainfall maps forecasted by WRF model were compared with rainfall accumulations recorded by the Sicilian weather stations. The comparison shows a good agreement between the predicted maps and observed data.

1. Introduction

The issue of climate change on the global scale, currently one of the most discussed topics in the international scene, is closely related to numerous and important repercussions on the weather conditions observed on a local scale, such as the development of extreme weather events.

On the other hand, a proper establishment of a well defined correlation between climate changes and extreme events is not straightforward and many efforts are currently being performed in this direction (Diffenbaugh *et al.* 2017; Faranda *et al.* 2022). For example, AR6 reports of the IPCC (IPCC 2021), address the issue linked to the general consensus towards the dependence between climate, ecosystems and biodiversity and human societies, recognizing the impact of climate change, caused by anthropogenic factors, on frequency and intensity of climatic and meteorological events, heavy rainfall, drought and fires.

With extreme weather events, one refers to two kinds of phenomena (M. Giuliacci, A. Giuliacci, and Corazzone 2003; Field and et al 2012): the first one indicates an event of exceptional violence (such as hurricanes, thunderstorms, or floods) occurring in a short amount of time. But there are also phenomena taking place on remarkably longer time intervals which in itself do not show extreme nature but, overall, can generate serious consequences, such as landslides, droughts, or melting glaciers.

One of the most effects noticeable of climate changes, in recent decades, is global warming (X. Liu, Vedlitz, and Alston 2008). In this context, the year 2021 was the fifth hottest year ever recorded. The hottest year ever recorded so far has been 2016 (Nita *et al.* 2022). In addition, intense heat waves were recorded during the summer of 2021 in Europe. In particular, on 21st June 2021, the presence of an anticyclonic field of subtropical matrix, which stationed for several days on the central Mediterranean, bringing general conditions of atmospheric stability and temperature everywhere well above the climatic averages of the period, due to the influx of warm winds from the southern quadrants.

On that date, several absolute records were exceeded for the thermal values observed by the network of meteorological stations supplied to the Servizio Informativo Agrometeorologico Siciliano (SIAS) in western Sicily, a region located at the southern Italian Peninsula (see Fig. 1).

FIGURE 1. Map showing the position of Sicily in southern Italy (modified from Google Earth).

The aforementioned records, referring to the 2002-2021 historical series, exceeded in Sicily concern 4 stations out of a total of 96 belonging to the SIAS detection network. These recorded values are shown below:

- Partinico with 42.9 °C, against a previous absolute maximum of 42.6 °C of 25/06/2007;
- Castellammare del Golfo with 42.8 °C, against a previous absolute maximum of 42.3 °C, of 06/08/2012;
- Trapani Fulgatore with 42.1 °C, against a previous absolute maximum of 41.5 °C of 07/08/2012;
- Agrigento Mandrascava with 39.6 °C, against a previous absolute maximum of 39.4 °C, 09/08/2012.

An additional heat wave was recorded in August 2021. Indeed, on 11 August, Italy was affected by the presence of a vast anticyclonic field of North African origin in action on the Mediterranean. This synoptic framework favored the ascent of warm air masses from the Sahara desert, thus recording high thermal values in the southern regions of Italy and, in particular, in Siracusa city, where the highest temperature ever recorded in Europe was reached, equal to 48.8 °C (Merlone *et al.* 2021)(see Fig. 2).

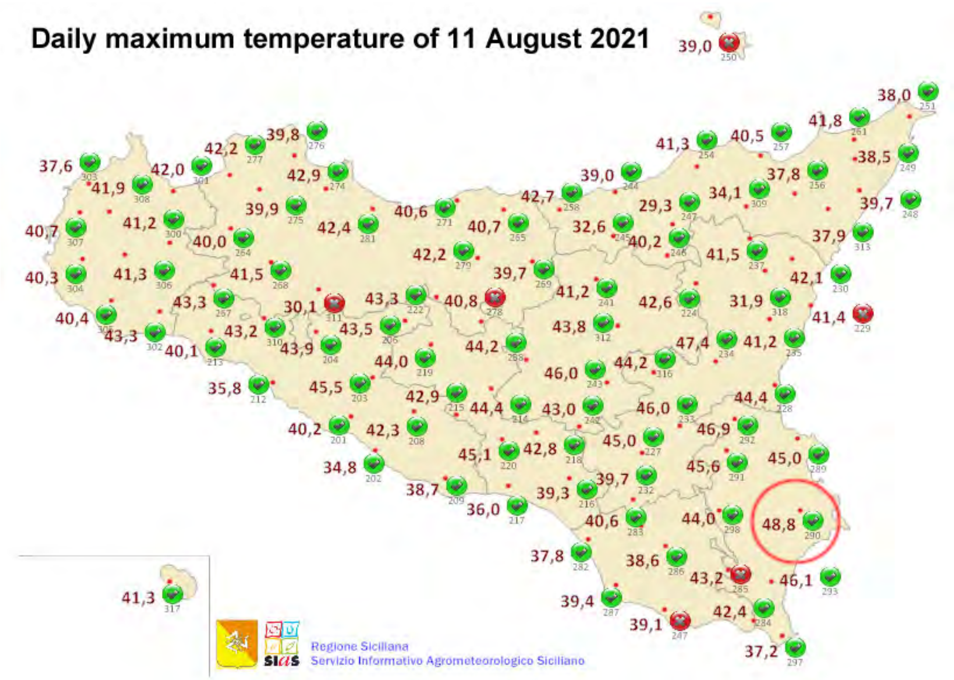

FIGURE 2. Daily maximum temperature recorded from SIAS weather stations network on 11 August 2021.

The connection between the global warming and the genesis of extreme weather events is particularly evident in the Mediterranean area (Sànchez *et al.* 2004; Garcia-Herrera, Lionello, and Ulbrich 2014),especially in Sicily (Forestieri *et al.* 2017; Mylonas *et al.* 2019). In this framework, a fundamental role is played by the increase of the Sea Surface Temperature (SST). Therefore, in order to highlight the upward trend of the SST in the Mediterranean Sea (García-Monteiro *et al.* 2022; Juza, Fernàndez-Mora, and Tintorè 2022), the marine climate data observed in Lampedusa (see Fig. 3) were reported. The peculiar geographical position of Lampedusa island makes it a natural hotspot on the Mediterranean Sea for Climate Change studies. These data were recorded by a station belonging to the Rete Mareografica Nazionale (RMN), managed by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) (available at https://www.mareografico.it/).

FIGURE 3. Map showing the position of Lampedusa mereographic station (red marker) and Panarea seafloor observatory (light blue marker). Figure modified from Google Earth.

Figure 4 shows the charts of sea surface temperature from January 2010 to December 2022.

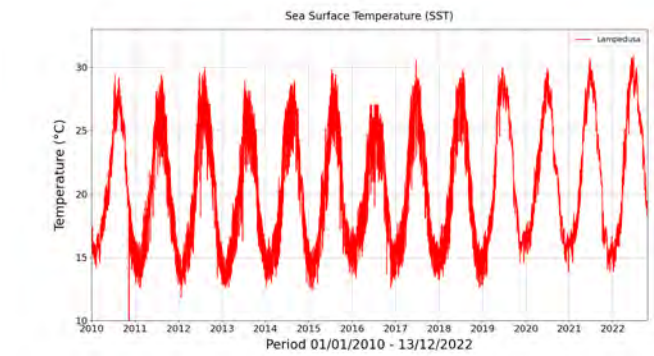

FIGURE 4. Upward trend of sea surface temperatures (period January 2010 – December 2022) observed by the Lampedusa station (data available online on ISPRA website).

The considered stations show an upward trend for the study period, both from maximum and minimum values.

Moreover, since the upward thermal trend recorded in the Mediterranean Sea does not concern only surface temperatures, data acquired by a multidisciplinary submarine observatory installed 2 miles off Panarea Island (Aeolian Archipelago, Southeastern Tyrrhenian Sea, see Figure 3) were reported. This submarine facility, managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Palermo (Italy), is composed by an observatory placed on the seafloor (right in Fig. 5), at depth of about 23 m (Romano *et al.* 2019; Longo *et al.* 2021; Caruso *et al.* 2022), connected to a pole beacon (left in Fig. 5). The chemical-physical parameters detected, in near-real time, are: pH, conductivity, hydrostatic pressure, temperature, CO_2. The sensor set is completed with hydrophone, Ocean Bottom Seismometer (OBS) and IP Camera. In addition, on the surface meteorological data were recorded.

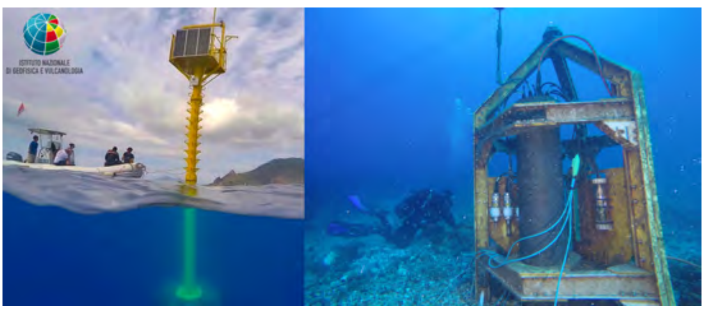

FIGURE 5. Pole beacon (left) and multidisciplinary submarine observatory (right) installed close to the Panarea coast.

The performed analysis concern the sea temperature during the autumn periods, from 2016 to 2021. Even in this case, the result shows an increase in the trend of thermal values, especially during November and December (see Figure 6).

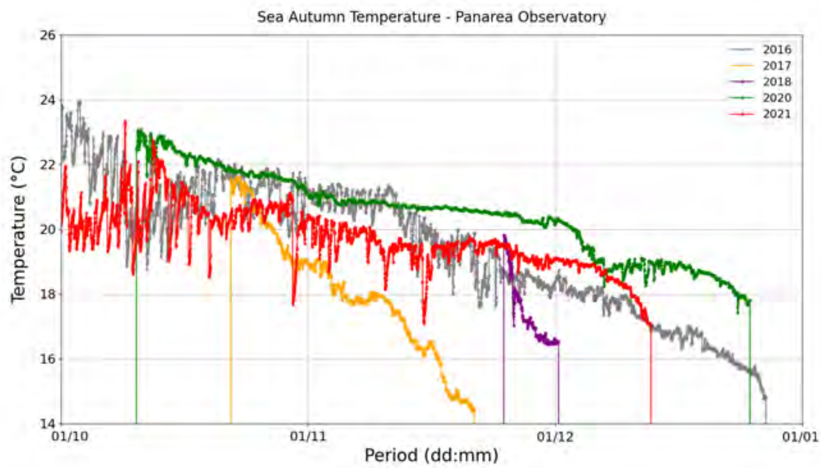

FIGURE 6. Chart showing the upward trend of the autumn sea temperature from 2016 to 2021.

Indeed, in Sicily a clear increase of extreme weather events, such as huge pluviometric accumulations highly localized in time and space, has been observed (Castorina *et al.* 2022). Among these, as an example, it is possible to mention the flood events that occurred on: 1 October 2009 (Scaletta Zanclea (ME) and southern districts of Messina); 22 November 2011 (Barcellona Pozzo di Gotto (ME), Merı‘ (ME) and Saponara (ME)); 3 November 2018 (Casteldaccia (PA)); 15 July 2020 (Palermo); 8 August 2020 (Messina, Terme Vigliatore (ME) and Barcellona Pozzo di Gotto (ME)); 24–29 October 2021 (Catania and Siracusa provinces).
In the course of these phenomena, precipitations occurring in few hours can exceed the rainfall usually registered in more than a month.

Furthermore, the complex orography that characterizes Sicily (see Fig. 7) causes the forced ascent of the air masses, in correspondence with the mountain ranges, favoring the genesis of intense pluviometric events (Caccamo *et al.* 2017b). The thermodynamic processes involved can be theoretically studied through various experiments, including the Rüchardt experiment (Caccamo *et al.* 2019) and the procedures based on the main frequency analysis techniques (Castorina, Caccamo, and Magazù 2018; Semprebello, Magazù, and Caccamo 2021). In addition, it is possible to include the effects caused by the presence in the atmosphere of natural pollutants (e.g. tephra and volcanic gases) by using the WRF-Chem model. (Grell *et al.* 2005; Rizza *et al.* 2020; Rizza *et al.* 2021; Castorina *et al.* 2023b; Rizza *et al.* 2023).

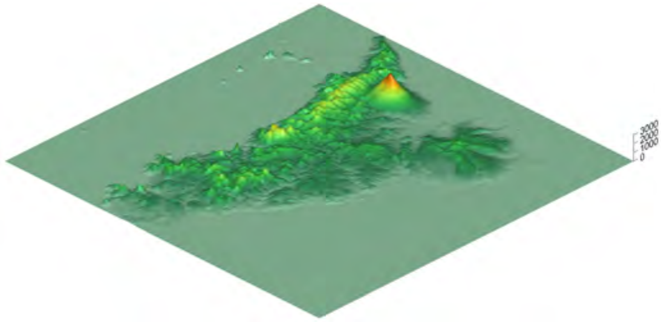

FIGURE 7. Map showing the complex orography of Sicily.

In addition, in the sea waters that lap the Sicilian coasts, the phenomenon of Medicanes is occurring (Miglietta *et al.* 2011): these are real Mediterranean hurricanes, with strongly similar characteristics to tropical cyclones (Miglietta *et al.* 2013, 2017), and therefore they can be seriously dangerous. The increase of the intensity of these phenomena is related to the increase of the surface sea temperatures (SST), as shown in recent studies (Pytharoulis 2018).

A further aspect of the connection between climate change and extreme events in Sicily concerns the rainfall: although the trend of annual values recorded in Sicily in recent decades shows a general increase in rainfall quantities, also an increase in drought periods has been observed. This translates into a decrease in the percentage of rainy days recorded annually. Consequently, the rainy events show greater intensity and more often erosive rains are observed (Caccamo *et al.* 2017a).

In this framework, the aim of the study was to analyze the severe meteorological event recorded at the end of October 2021, which affected eastern Sicily. In particular, the Medicane called Apollo (Borzi *et al.* 2022; Lagasio *et al.* 2022; Menna *et al.* 2023; Piroddi *et al.* 2023) (Fig. 8, available from the link dataset (MODIS Atmosphere Science Team 2017): http://doi.org/10.5067/MODIS/MOD06_L2.NRT.061) was taken as a case study.

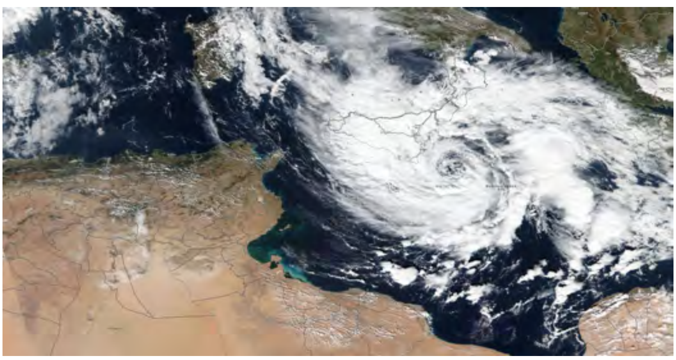

FIGURE 8. Apollo Medicane detected by the Terra MODIS satellite on 29 October 2021.

2. The Weather Research and Forecasting Model

In the present work the numerical simulation has been performed by using the Weather Research and Forecasting model (W. Skamarock and J. Klemp 2008), developed inside the collaboration among the National Center for Atmospheric Research (NCAR), the National Center for Environmental Prediction (NCEP) and the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA). The central core of the model, named WRF Software Framework, is constituted by different schemes of assimilation and parameterization of physical variables and is connected to pre- and post-processing modules. The first one, named WPS, includes the subroutines Geogrid, Ungrib and Metgrid, which create static data, including geographic and land-use data, assimilate meteorological data collected by global computing centers and interpolate these data on a numerical domain, respectively.

In particular, the subroutine Geogrid interpolates land use data from Moderate Resolution Imaging Spectroradiometer (MODIS) IGBP 21-category data (Salomonson *et al.* 1989).

The resulting time-dependent fields include water vapour, winds and potential temperature in 3D, with also additional 2D surface fields.

Pre-processed data are then analyzed by the software WRF-REAL, which interpolates them along a certain number of vertical levels, keeping into account the spatial coordinates adopted.

Simulation run are then performed by the WRF software, whose output are finally plotted and analyzed through suited graphical programs, such as NCVIEW, GRADS and NCL. Two different cores are available to run the WRF model, specifically the ARW core (W. C. Skamarock *et al.* 2019b), developed by NCAR and capable to simulate different kinds of meteorological events with different degrees of spatial resolution, and the Non-hydrostatic Mesoscale Model (NMM) (Z. Janjic *et al.* 2014), developed by NCEP, able to work in both hydrostatic and non-hydrostatic mode (Bernardet *et al.* 2009).

In the present work, the 4.1.2 version of the WRF model (available at the following link: https://www2.mmm.ucar.edu/wrf/users/wrf_files/), with the ARW core, has been implemented. The model has been optimized for Sicily, a region characterized by a complex orography (Castorina *et al.* 2017; Colombo *et al.* 2017), and the physical parameterizations were chosen based on the results obtained in the case studies previously treated (Castorina *et al.* 2018; Castorina, Caccamo, and Magazù 2019; Castorina *et al.* 2021, 2023a). Initial and boundary conditions have been built by using the Global Forecast System (GFS) model with an horizontal resolution of 0.25 degrees and a time step of 1 hour (available at the following link: https://soostrc.comet.ucar.edu/data/grib/gfsp25/); such conditions have been processed starting from 00:00 UTC of 29 October 2021.

Sixty-five vertical levels, up to 50 hPa, were selected. Among input data, also the SST have been provided, by means of the Real-Time Global Sea Surface Temperature (RTGSST), with a resolution of 0.083 degrees (available at the following link: ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/gfs/prod).

The domain selected (see in Fig. 9) in this case study was obtained by the nesting protocol (Daniels *et al.* 2016). According to this technique, it is possible to implement a large parent domain to obtain a second nested domain with higher spatial resolution and therefore a finer spacing grid. The nesting procedure allows to focus on the areas of the domain of high interest, solving the primitive equations in their finer grid. In the present study, the one-way nesting configuration has been adopted: in its framework, information travels unidirectionally from the parent domain to the nested domain, without coming back. The simulation of the parent domain is performed first; the obtained outputs provide the boundary conditions for the nested domain, processed in the subsequent step. In particular, starting from a parent domain with resolution of 9 km, a nested domain with horizontal spatial grid resolution of 3 km has been obtained.

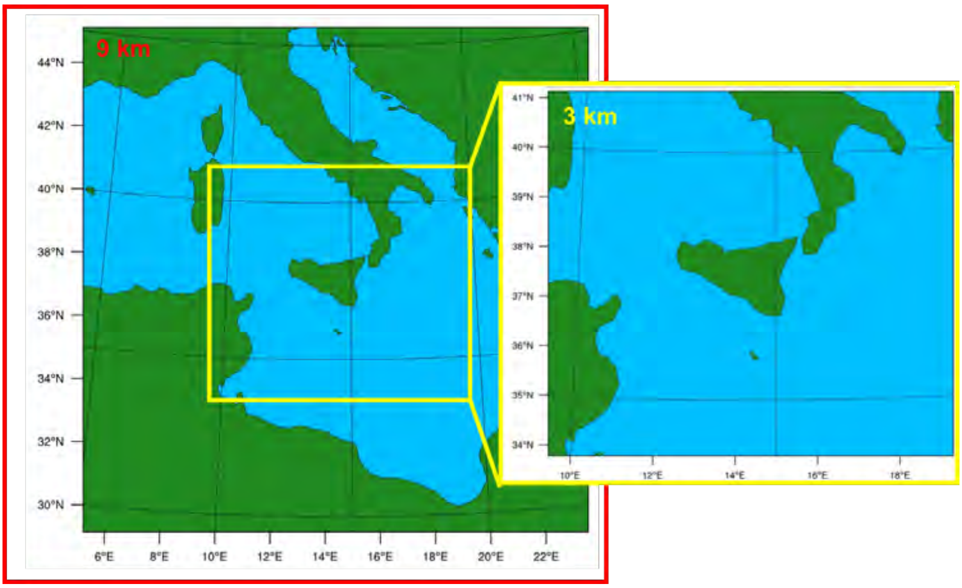

FIGURE 9. Representation of the nested domains adopted in this work. Starting from a parent domain with a resolution of 9 km (left), a nested domain of 3 km has been built (right).

3. Results of the simulation

The aims of this work is to evaluate the capability of the WRF model in forecasting rainfall accumulations and wind conditions due to Apollo Medicane. In particular, starting from 00:00 UTC on 29 October 2021 and for the following 48 hours, the precipitation forecasts and the wind at 10 meters obtained from the simulation will be evaluated. In this context, the simulation was performed by adopting a spatial grid resolution of 3 km, obtained through the nesting tecnique. The map of rainfall accumulation predicted in 24 hours shows that the most intense rainfall affected the eastern sector of Sicily and, in particular, the province of Siracusa. In this area, the simulation forecasted values of total rainfall accumulation up to about 300mm/24h (see Fig. 10).

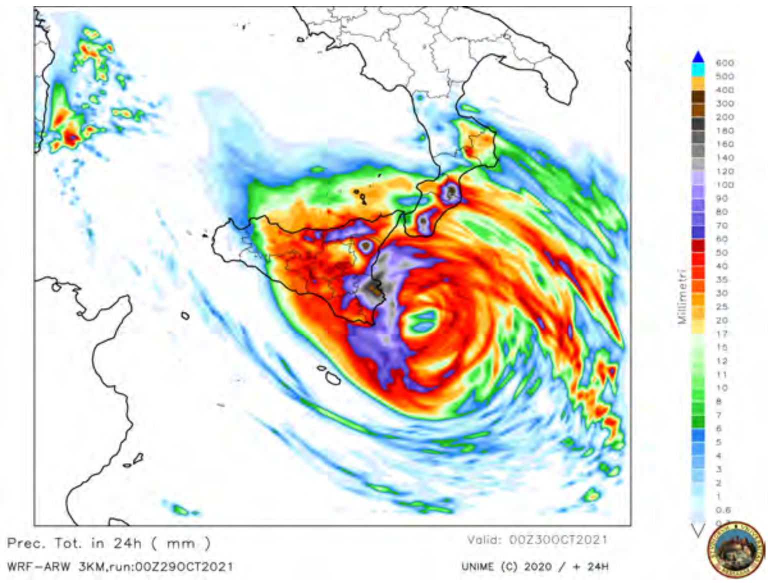

FIGURE 10. Rainfall accumulation (in mm) in the 24 hours from 00:00 UTC of 29 October 2021 to 00:00 UTC of 30 October 2021.

This result is in good agreement, both in pluviometric accumulations and in spatial localization, with the data observed (see Fig. 11) by the network of meteorological stations of the Regional Department of Civil Protection of the Sicily Region (DRPC-Sicily).

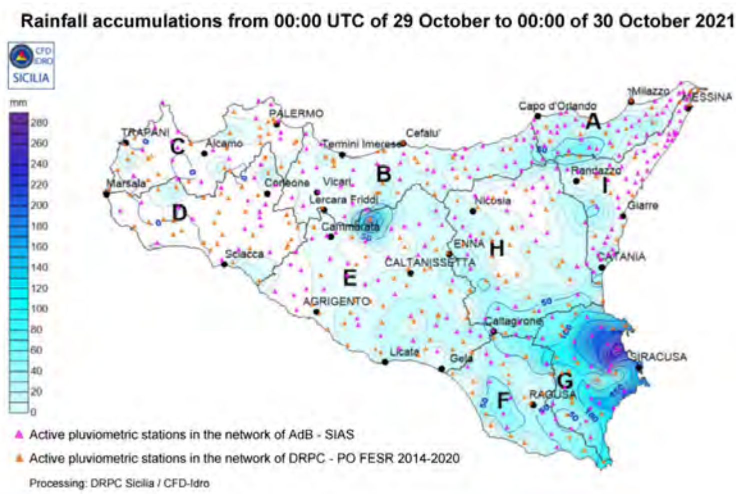

FIGURE 11. Cumulative rainfall (in mm) observed in the 24 h from 00:00 UTC of 29 October 2021 to 00:00 UTC of 30 October 2021.

Moreover, in order to show the Medicane tracking predicted by the WRF model, in the following figures the maps of the forecasted rainfall accumulations every 6 hours (Fig. 12) and the maps of wind direction and speed at 10 meters (Fig. 13), are shown.

In particular, in Fig. 12, it is possible to see that the most intense phenomena were expected, especially in the first 12 hours, on the Siracusa area. For example, rainfall accumulations close to 120 mm/6h, were expected (panel b)). In panels e) and f) the gradual away of the Medicane from Sicily is visible. In Fig. 13, it is possible to see that the maximum wind speed expected near the eastern coastal areas of Sicily was about 80-90 km/h, with values close to 100 km/h at sea (panel a)).

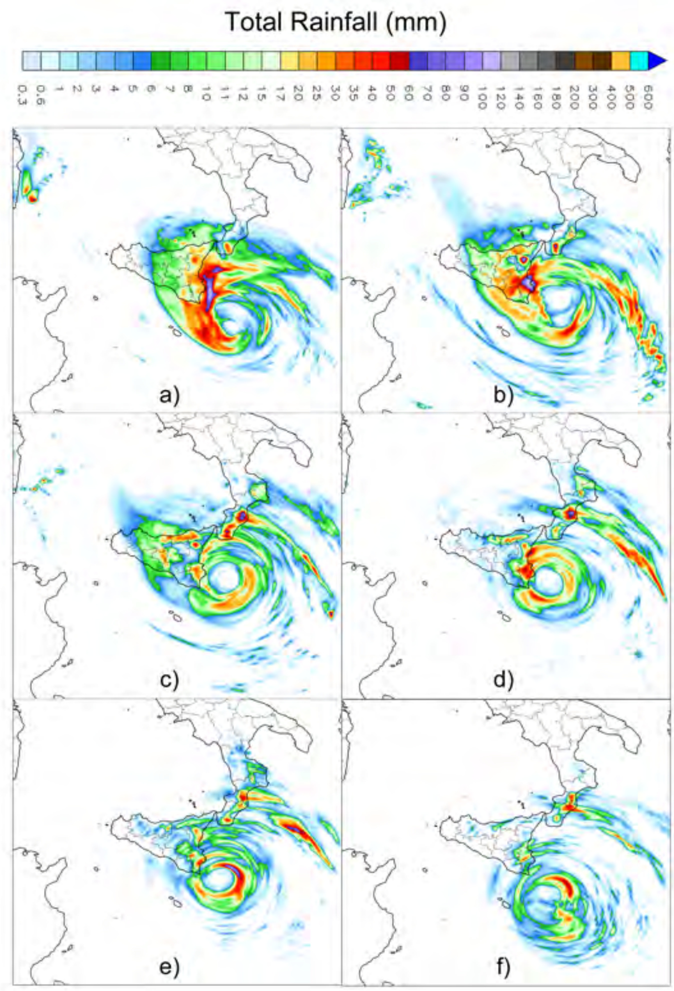

FIGURE 12. Rainfall accumulations (in mm) every 6 hours from 06:00 UTC of 29 October 2021 (a) to 12:00 UTC of 30 October 2021 (f).

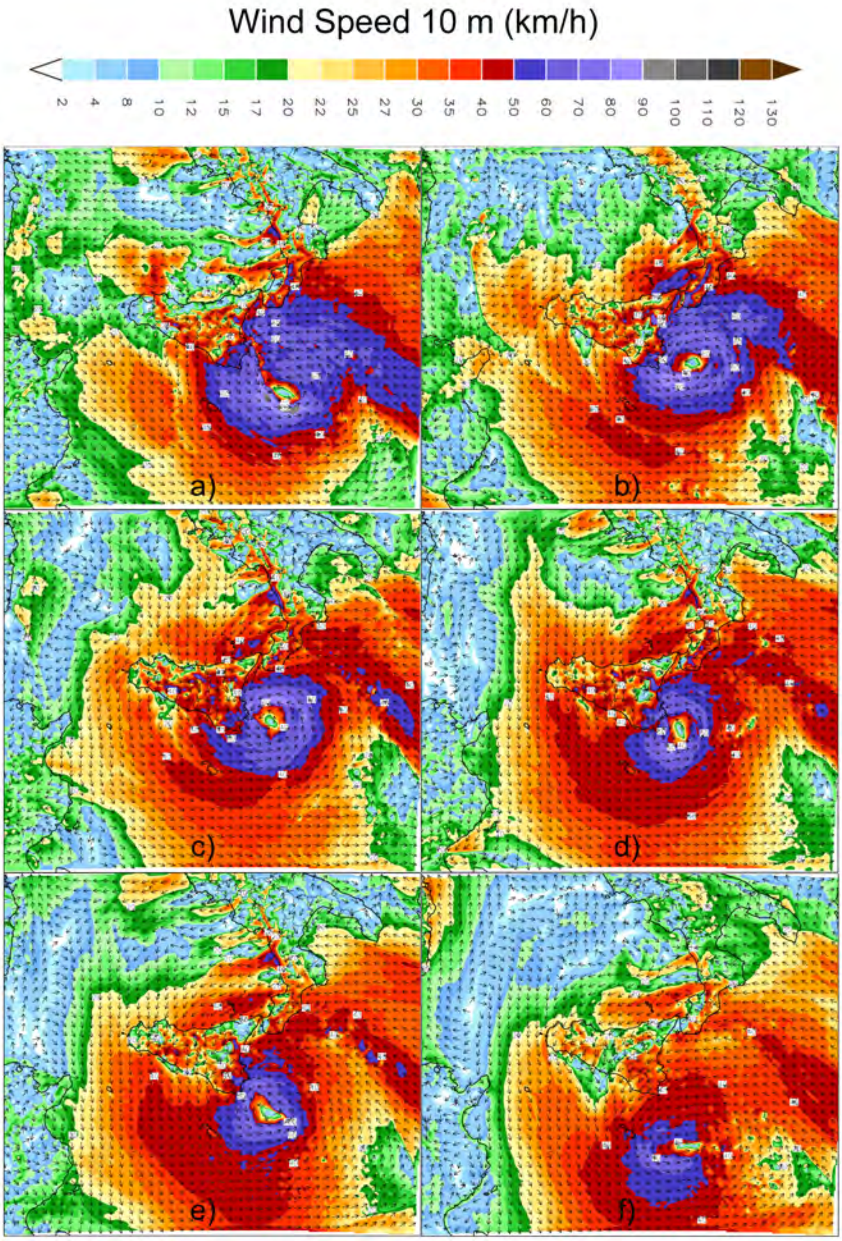

FIGURE 13. Wind direction and speed (in km/h) every 6 hours from 06:00 UTC of 29 October 2021 (a) to 12:00 UTC of 30 October 2021 (f).

4. Conclusions

This study aimed to employ the WRF model for reproducing the extreme weather conditions associated to the Apollo Medicane, which affected the eastern part of Sicily (southern Italy) in the last days of October 2021. Particularly, the rainfall accumulations forecasts were analyses. The results of simulation were compared with data observed by DRPC-Sicilia network of weather stations. Moreover, in order to show the simulated tracking of Apollo, the precipitation and wind maps at 6-hour intervals were reported. The analyzes were carried out by using the WRF model, with a resolution of the horizontal spatial grid of 3 km, specifically optimized for the Sicily region. In particular, the maps of the total precipitation forecast in 24/h, the precipitation maps at 6-hour intervals and the wind maps every 6 hours, are shown. The obtained results show a good agreement between the rainfall accumulations forecasted by the WRF simulation and data recorded by the network of meteorological stations of DRPC-Sicily.

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