Mediterranean Cyclone Daniel, 3 – 11 September 2023

Updated report – 26 September 2023

Summary

This report provides an overview and assessment of the high-impact weather event, Storm Daniel, which occurred from September 3 to September 11, 2023 in the eastern Mediterranean. Storm Daniel was a powerful and destructive Mediterranean cyclone that impacted several countries, mainly Greece, Bulgaria, Turkey, and Libya. About 20,000 casualties have been reported in Libya, 15 in Greece, and 10 in Bulgaria and Turkey.

Storm Daniel seems to be an exceptionally rare event and has been characterized by some sources as a Medicane ("Mediterranean hurricane"), although this categorization will need a detailed meteorological analysis. Its formation is attributed to climate variability and the unseasonable undulation of the jet stream, the causes of which have yet to be thoroughly investigated. Preliminary results based on weather analogues, show that human-induced climate change has increased the intensity of such storms in recent years (IPCC, 2023 - Sections 11.7 & 12.4).

This report covers the event's timeline, meteorological characteristics, and impacts.

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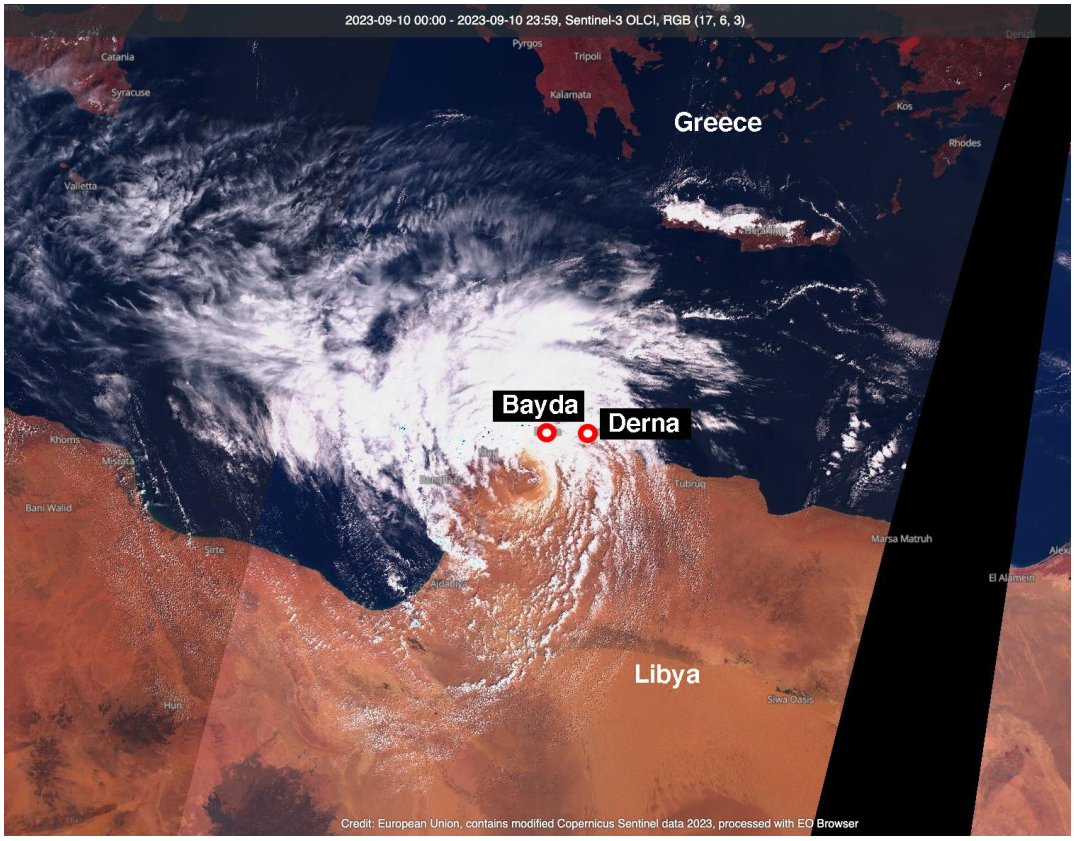

Fig. 1 Satellite image of Storm Daniel on 10 September 2023. Courtesy of Copernicus, European Union.

Event Timeline

- **Formation:** Storm Daniel originated with a Mediterranean depression in the Ionian Sea on Monday 4 September 2023. An omega-blocking pattern was in place over Europe, when a cut-off low formed in central Europe, along the eastern flank of the high-pressure system. This occurred through Rossby wave breaking (the irreversible undulation of the jet stream) and the cut-off low subsequently entered the Mediterranean, promoting cyclogenesis.

- **Floods in Greece, Turkey, and Bulgaria:** On Tuesday 5 September 2023, the position and the slow southward movement of the cyclone in the Ionian Sea, established a persistent easterly/northeasterly flow of warm and moist air masses over the Black and Aegean Seas, where several convergence zones created long-lasting training convection. High accumulations of rainfall were observed in Greece by the network of the National Observatory of Greece/meteo.gr, where more than 750 mm of daily

rainfall were recorded, and up to 1235 mm within 4 days. In Bulgaria, about 311 mm of rainfall was recorded within 14 hours.

- **Intensification:** Severe weather events gradually faded in Greece during the night on Thursday 6 September 2023. The surface cyclone was in phase with the mid/upper-tropospheric low, while frontal activity started to be less pronounced. In the following 3 days, Storm Daniel intensified over the warm Mediterranean Sea in terms of wind speed close to the center, with sustained winds up to 40 kts (74 km/h) based on satellite data. Also, deep moist convection started to be more active close to the cyclone center. The cyclone progressively evolved from a baroclinic to a barotropic system while slowly moving southward.

- **Landfall:** Storm Daniel reached the northeastern coasts of Libya during the night hours of Saturday, 9th of September 2023. In Bayda, about 414 mm of rainfall were recorded within less than 24 hours, an amount that is equal to 80 % of the city's mean annually accumulated precipitation. Before landfall, based on satellite and numerical data, it seems that Storm Daniel was a warm-air seclusion over the Gulf of Sidra, depicting a structure similar to subtropical cyclones in other oceanic basins, and evolved to a tropical-like cyclone in the afternoon on 9th September. This similarity has motivated the characterization of the cyclone as Medicane.

- **Dissipation:** Storm Daniel resulted in severe flash floods in northern Libya and dissipated over the Sahara desert when it reached Egypt on Monday, 11th of September 2023, since it was not fed anymore by the warm sea surface. Ancient salt lakes in the Sahara Desert were also flooded. During the dissipation phase there were very strong surface currents on arid areas in the border between Libya and Egypt that mobilized high amounts of aeolian dust and transported them towards the Eastern Mediterranean. This can be clearly seen in the MODIS (Terra and Aqua) Combined Value-Added Aerosol Optical Depth (AOD) values from MODIS Level 2 aerosol products and verified by AERONET AOD measurements in ground stations such as Sede Boker in Israel (Fig. 2).

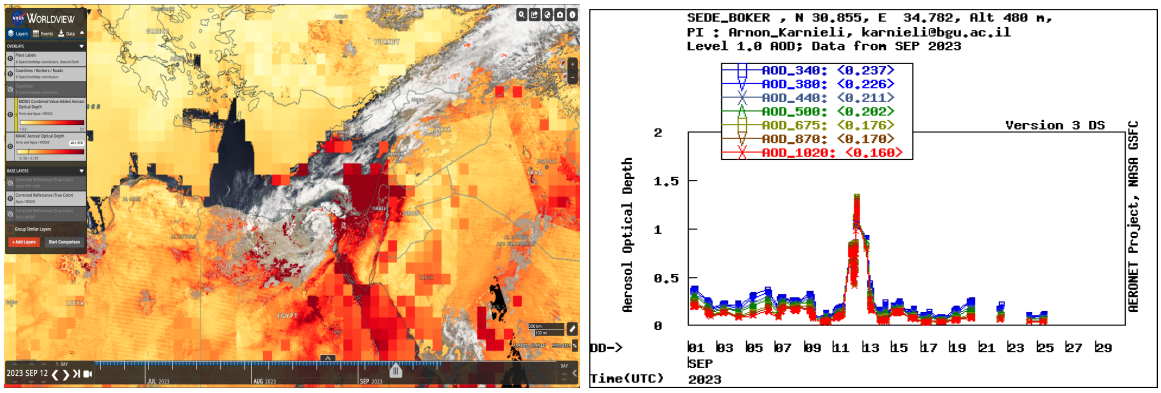

Fig. 2 Aerosol Optical Depth (AOD) values from MODIS Level 2 aerosol products for September 11th, 2023 (left plot) and AERONET AOD measurements in Sede Boker ground station in Israel (right plot) for the month of September 2023. Imagery from the NASA Worldview application (https://worldview.earthdata.nasa.gov/), part of the NASA Earth Observing System Data and Information System (EOSDIS) and AOD image available from the AERONET web site (https://aeronet.gsfc.nasa.gov).

Impacts

Human Impacts:

- According to the Libyan Red Crescent, Storm Daniel caused 11,000 confirmed fatalities and 10,100 people are still missing (until 22 September 2023). About 4,000 people have been injured and survivors suffer psychological traumas.
- Evacuation orders were issued, leading to the displacement of 9,047 residents in Central Greece. According to the United Nations, more than 43,000 people have been displaced.
- Significant power outages affected millions of people.
- Remaining swamp muddy areas pose concerns for water quality and other health related conditions.

Infrastructure and Property Damage:

- Widespread structural damage to homes, businesses, and public buildings. About 50 buildings have collapsed in Greece and more than 900 in Libya. Using the Google Building database and the satellite observations of the flood extent, 939 have been completely damaged, 4,215 buildings have been flooded and covered with mud, and about 1,219 have less damage.

- Flooding damaged roads, bridges, and other critical infrastructure in all affected countries.
- Coastal communities experienced erosion and marine submersion.

Agricultural and livestock Impact:

- Crop damage, particularly to cotton, corn, and apples, was extensive.
- The storm disrupted fishing and aquaculture operations.
- More than 220,000 animals in Greece used as livestock, have been declared dead.

Economic Impact:

- Estimated economic losses from Storm Daniel exceeded $4 billion, including insured and uninsured losses.
- According to the Hellenic Association of Insurance Companies, 6,011 insured assets have been damaged only in Greece (until 21 September).
- The humanitarian crisis in place in Libya has also strong implications for economic challenges over the long term.

Preliminary Satellite Analysis

The MedCyclones Working Groups have started analyzing all the available satellite and numerical data for the Mediterranean Storm Daniel. First, data from the Advanced Microwave Sounding Units and Microwave Humidity Sounders on board satellites NOAA-19, NOAA-20, NOAA-21, and MetOp-C were analyzed to better understand the vertical structure of Storm Daniel. Based on the method that was developed by Panegrossi et al. (2023), we are able to detect the warm core of the cyclone before the landfall in Libya visible around the white dot in Figure 3 as positive Brightness Temperature (TB) anomalies. The cold TB anomalies at the lower levels indicate the presence of deep moist convection in proximity to the cyclone center.

Even though the vertical extent and intensity of the warm core is similar to previously documented Medicanes, further investigation is needed to explain the thermodynamic processes that contributed to this feature.

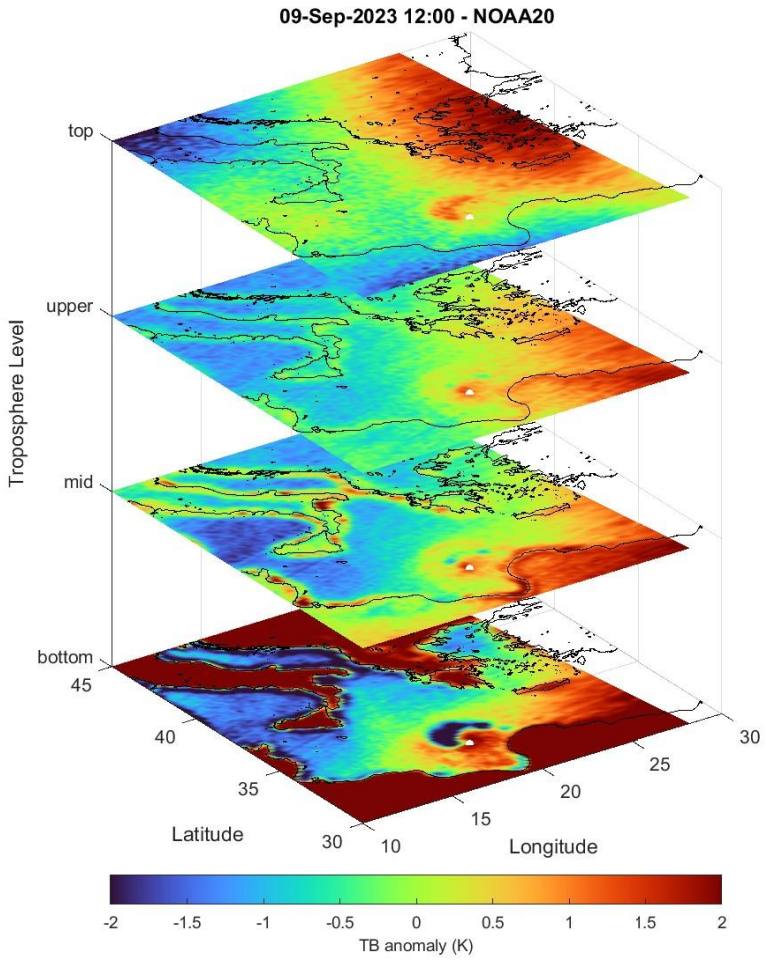

Fig. 3 Brightness temperature anomalies (K) NOAA-20 on 9 September 2023, at 12:00 UTC. The white dot indicates the position of the minimum sea-level pressure.

Scatterometers onboard the European satellites MetOp-B and MetOp-C provide information about the wind speed and direction close to the sea surface. In Figure 3, we show an example of the quasi-symmetric structure of the cyclone close to the coasts of Libya on 9 September 2023. Maximum wind speeds close to the cyclone center on 9 September 2023 reached values close to 76 km/h in the western side, and much lower values (~50 km/h) in the east and north parts (Fig. 4). A strong convergence zone was evident in scatterometer data during the flooding (not shown).

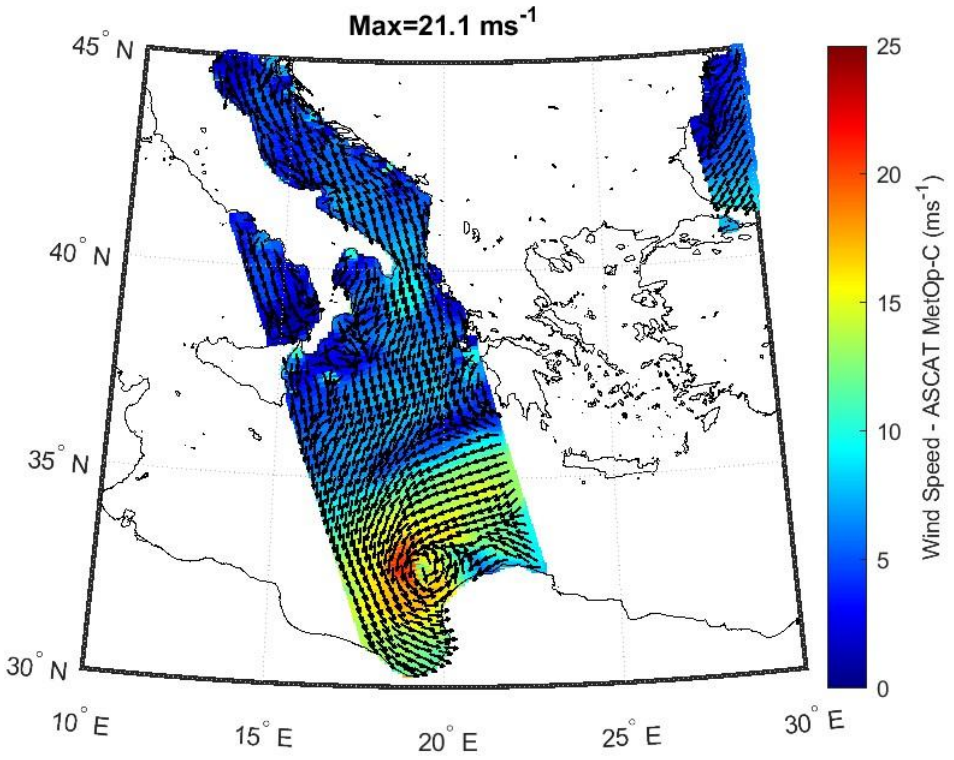

Fig. 4 Surface wind speed and direction estimation provided by the scatterometer onboard MetOp-C on 9 September 2023, at 19:21 UTC.

A third analysis using sea surface temperature (SST) data from the Copernicus Marine Service estimated the SST change between 3 and 15 September 2023. In Figure 5, it is evident that Storm Daniel had a large impact on the sea, with a significant SST drop in the whole Ionian Sea and Gulf of Sidra. This SST drop might have originated from different processes of atmospheric and/or oceanic origin and needs to be investigated in depth in order to understand the ocean-atmosphere interaction during Storm Daniel.

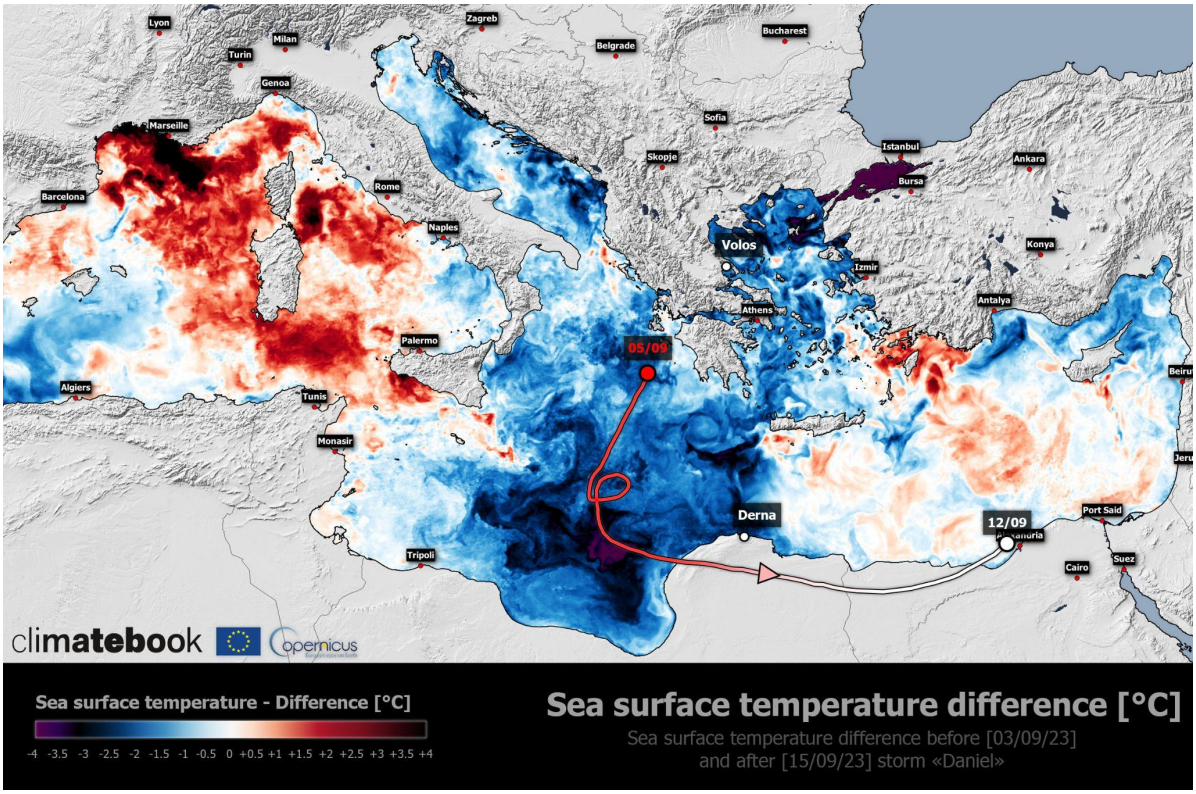

Fig. 5 Sea surface temperature difference between 3 and 15 September 2023. The red/white line indicates the track of Storm Daniel between 5 and 12 September 2023. Courtesy of Climatebook.gr, using Copernicus Marine Service data.

Conclusion

Storm Daniel was a high-impact weather event that caused unprecedented loss of life, damage, and destruction along Mediterranean countries. The numerous casualties and widespread destruction in Greece, Bulgaria, and Turkey stressed out systematic problems in preparedness and response strategies by the governments. In the case of Libya, according to WMO, although a weather warning for heavy rain was issued one day in advance by the National Meteorological Agency, blockages in the warning value chain meant no evacuation happened. Two dams collapsed and generated widespread destruction downstream in Derna, where most of the casualties happened. This lack of preparedness resulted in one of the deadliest weather-related events in recent history.

Preliminary analysis of satellite data shows that Storm Daniel was an extratropical cyclone over the Ionian Sea, turning into a Subtropical Cyclone in the Gulf of Sidra, with brief Tropical-like

Cyclone characteristics a few hours before landfall in Libya. Similar “hybrid” cyclones have been documented in the past, and pose a serious threat to Mediterranean countries.

Such high-impact events make evidence on the governments’ necessity to invest in infrastructure improvements to mitigate storm-related damage, such as reinforcing levees and flood defenses. It also suggests the urge to conduct outreach programs to educate residents about storm preparedness and evacuation procedures. Moreover, significant improvements in coordination between federal, state, and local agencies are needed, to streamline disaster response efforts.

Recognizing the scientific evidence that the intensity of Mediterranean storms is increasing (IPCC, 2023 - Sections 11.7 & 12.4), developing adaptation measures in response to the impacts and establishing long-term climate change mitigation strategies are vital steps of utmost importance for sustaining a viable environment for the Mediterranean. To this direction, the European Cooperation in Science and Technology (COST) Action MedCyclones (https://medcyclones.eu/) promotes networking between scientists and stakeholders to advance our understanding on Mediterranean cyclones and to effectively exploit fundamental research outputs for the benefit of the society.

References

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2. IPCC, 2023: *Climate Change 2023: Synthesis Report.* Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, https://doi.org/10.59327/IPCC/AR6-9789291691647

Link to the first version of the report

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