Storm Daniel revealed the fragility of the Mediterranean region

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Over the past two years, the world has witnessed a surge in extreme events, including record-breaking droughts, heatwaves, forest fires, floods, ocean warming, and sea ice melting. These events have affected large regions, with devastating droughts striking Europe, East Africa, Asia, and South America, historic floods hitting Pakistan, and unprecedented heatwaves scorching western North America. Major wildfires have ravaged areas in Algeria, southern Turkey, Greece, and Spain, while the Arctic and Antarctic continue to experience alarming sea ice melt.

Drought-flood abrupt alternation in the Mediterranean basin

The Mediterranean basin emerged as one of the most critical hotspots. Among the several disasters that occurred, this region faced unprecedented drought and heatwave in 2022. This was followed by another intense heatwave episode in 2023, combined with extreme rainfall, hailstorms, and flooding. The consequences were severe, and entire ecosystems and communities were threatened—drought, saltwater intrusion, hailstorms, and flooding severely impacted agriculture. For instance, in less than one year, two extreme phenomena occurred in Northeast Italy: the most severe drought of the last 200 years[1] and one of the most devastating floods (two events in 15 days in early May 2023, with more than 200 mm per event, and total 9 billion damages). Special attention, however, must be paid to the sea surface temperature (SST). In the summer of 2022, SST reached 5°C higher than average (compared to the averaged data during the same period from 1985 to 2005; https://www.esa.int/ESA_Multimedia/Videos/2022/09/Sea_surface_temperature_anomalies); such an anomaly has persisted since October 2022. In July 2023, it reached a +5.5 °C anomaly between North Africa, south of Italy and Greece (https://climate.copernicus.eu/global-sea-surface-temperature-reaches-record-high). High SST in the Mediterranean were a major factor behind the formation of the most fatal and expensive Mediterranean tropical cyclone recorded[2], Storm Daniel. On 4 September 2023, a low-pressure system moved inland across the Balkan

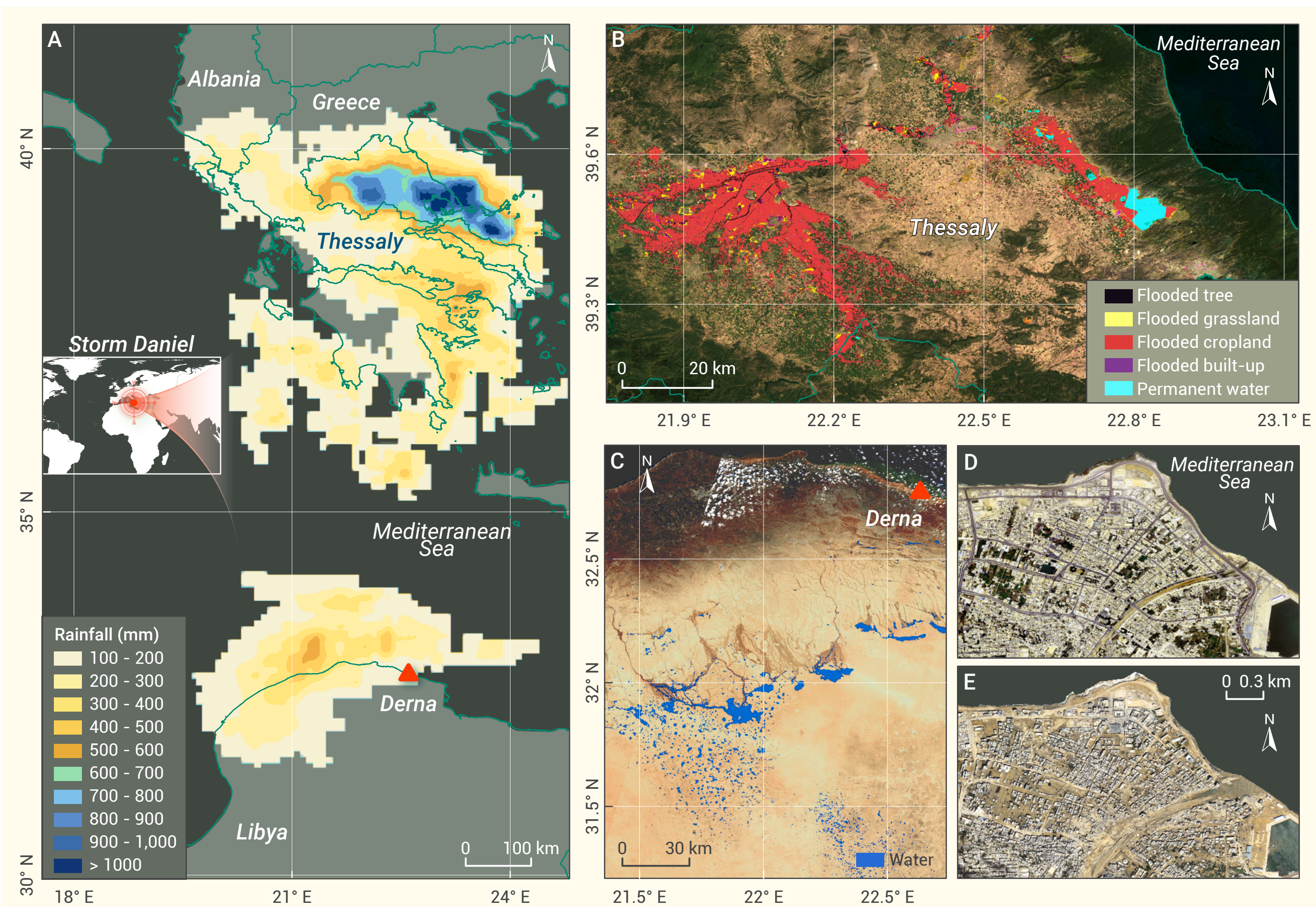

Figure 1. (a) Rainfall monitoring using GPM; (b) Flood monitoring in Thessaly region using S1 images from Sep 6th to 7th and L8 images on Sep 8th; (c) Flood monitoring in Libya using S2 images; (d) VHR image in Derna before the flood; (e) VHR image in Derna after the flood. GPM, S1, S2, L8, and ESA WorldCover 10m 2021 data were obtained from the Google Earth Engine platform. VHR images were downloaded from the Maxar Open Data Program (https://www.maxar.com/open-data). The method of flood monitoring using S1 refers to Qiu et al.[3]. MNDW (threshold > 0.2) was used to extract water bodies in S2 and L8 images[4].

Peninsula and caused heavy rainfall and severe flooding and damage, particularly in the Thessaly region. The system evolved into a Mediterranean cyclone in the following days and moved southeastward as a subtropical storm. On 10 September 2023, the storm hit the shores of Libya near the city of Benghazi but inflicted the most fatal damage in the city of Derna, with more than 11,000 confirmed casualties at the time of writing and an estimated 18-20,000 people affected. Near the coast of Libya, SST exceeded 27.5°C, resulting in increased energy for convection and moisture. This, in turn, fuelled and intensified the Daniel storm.

Storm Daniel: the catastrophic floods in Greece and Libya

Based on the Global Precipitation Measurement (GPM) v6 data (Figure 1a), from September 4th to 6th, 2023, most areas of Thessaly (Greece) experienced rainfall exceeding 400 mm. Remarkably, the central and eastern regions experienced rainfall exceeding 900 mm, more than Thessaly's annual average rainfall. According to the coordinated monitoring of Sentinel-1 SAR (S1) and Landsat 8 (L8) imagery, the observed flooded area in the Thessaly region was 875.28 km^2 (Figure 1b). The areas of flooded cropland, grassland, trees, and build-up were 740.72 km^2, 66.15 km^2, 47.34 km^2, and 12.14 km^2, respectively, accounting for 84.6%, 7.6%, 5.4%, and 1.3% of the total flooded area. The extensive damage to croplands threatens the economic livelihoods of local farmers and the region's food security.

On September 10th, Storm Daniel made landfall in northern Libya. Most areas saw rainfall between 100 and 400 mm, with some coastal regions receiving over 400 mm of precipitation. The unparalleled magnitude of rainfall has triggered massive flooding in the desert, a rare phenomenon. According to the water delineation in Sentinel-2 (S2) images, the inundated area in the desert was 1010.45 km^2, excluding the area of flood traces shown in Figure 1c. The hotspot of the affected area is Derna. The collapses of Derna and Mansour dam unleashed a 7 m wave of water slamming into the city of Derna (https://amp-cnn-com.cdn.ampproject.org/c/s/amp.cnn.com/cnn/2023/09/19/world/libya-floods-climate-change-impact/index.html), propelling buildings and people into the sea. Despite Derna receiving relatively less rainfall, over 11,000 casualties caused by a single flood event break the record in recent years. According to the Copernicus Emergency Management Service (https://www.copernicus.eu/it/node/30138), 3,925 buildings have been damaged, and 875 buildings have been destroyed (Figure 1d and 1e). Indeed, one study has ascertained a notable susceptibility to high flood risks within the Wadi Derna basin[5]. The findings underscore the imperative for periodic maintenance of the dams by the local authorities. However, in the context of a protracted civil war, the Libyan authorities have faced considerable challenges in upholding water infrastructure. Moreover, the deficiency of a flood warning system and the delay in implementing flood emergency measures have unfortunately escalated what could have been a preventable or mitigable crisis into a humanitarian catastrophe.

Urgent need for an effective climate change adaptation plan for the Mediterranean

The storm Daniel revealed the fragility of the Mediterranean region, especially for the arid and semi-arid areas. The shift of the traditional flood model from a single-driver event to a cascading event in which the heatwave preceding the storm formation amplifies the flood's negative impacts. Under the background, the hydrology, hydrometeorology, and hydroclimatology of flooding of these regions still need to be better understood. Because of the lack of hydrological observations in the arid and semi-arid areas, current hydrological models show poor ability for flood simulation in these areas, resulting in a poor representation of the driving processes and the risk map. Consequently, on the one hand, the locations that are highly vulnerable to the growing intensification of extreme rainfall cannot be well identified. Additionally, mitigation solutions are absent in the worst cases and, if present, obsolete since they cannot mitigate flooding under the actual climate conditions and rapid landscape urbanisation. On the other hand, socioeconomic conditions and geopolitical conflicts in low-income countries are leading to a lack of hydraulic infrastructure maintenance and communication during pre-event and real-time emergency evacuation procedures.

There is an urgent need to adopt an ad-hoc integrated watershed management plan for all the countries confined within the Mediterranean. There are better solutions than acting individually or looking only at the EU scale. An alliance among countries is necessary; a protocol to delineate a shared guideline must be developed. A failure in such actions would result in socioeconomic criticalities and even geopolitical tension because of possible massive migrations.

Capacity building is important to enhance climate change adaptation. First, there is a need for effective structural solutions to store the large amount of rainfall falling in a short time. Larger detention areas could be a way to follow; however, these need to have a low impact and be sustainable. Small-medium size rainwater storages could also work if located in hydrologically and topographically correct positions, especially on steep-slope agricultural landscapes where runoff events could trigger landslides. Nature-based solutions (NBS) offer an opportunity to improve resilience while preserving ecosystems. On this point, wetlands could play the role of detention basin; maintaining and re-establishing wetlands is a sustainable solution aligned with the 2030 Agenda for Sustainable Development. Second, the lack of maintenance, in most cases, is among the most evident reasons for disasters. It is necessary to have a shared Mediterranean scale protocol combined with an updated inventory of the most critical infrastructures. This is the most challenging goal to reach. If maintaining all the infrastructures is complicated in already developed countries, it is even more critical in low-income ones, and the actual global economic condition (e.g., inflation and high living costs) is not helping. We are convinced that a specific fund for disaster risk management for all the Mediterranean countries, without a distinction between the EU and North Africa, is urgently necessary.

Towards a Mediterranean scale early warning system

A further needed action is improving our ability to predict extreme events, particularly in less developed areas. This is an international priority, as demonstrated by the UN's Early Warnings for All programme (https://www.undrr.org/early-warnings-for-all). Space agencies and international institutions are working towards this goal. Satellite products for monitoring precipitation and other key variables for forecasting hydrological extremes (e.g., soil moisture, snow) are available in near real-time and at high resolution (e.g., Eumetview; https://view.eumetsat.int/productviewer?v=default). Integrating satellite products with advanced numerical weather prediction and hydrological modelling will allow the development of effective early warning systems even in poorly gauged areas where ground observations are lacking or difficult to access. We also emphasise that such systems should be (1) designed to detect different hazards that may occur alone, simultaneously, or in cascade - multi-hazard, (2) end-to-end, i.e., providing information from hazard detection to action, and (3) people-centred.

We aim for this commentary to encourage measures that reduce the risk of flooding in the Mediterranean region, ultimately saving lives and property.

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DECLARATION OF INTERESTS

The authors declare no competing interests.