

## DEVELOPMENT OF A MEDICANE-INDUCED LANDSLIDE INVENTORY; CASE STUDY OF 2023 CYCLONE DANIEL, CENTRAL GREECE

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### Abstract

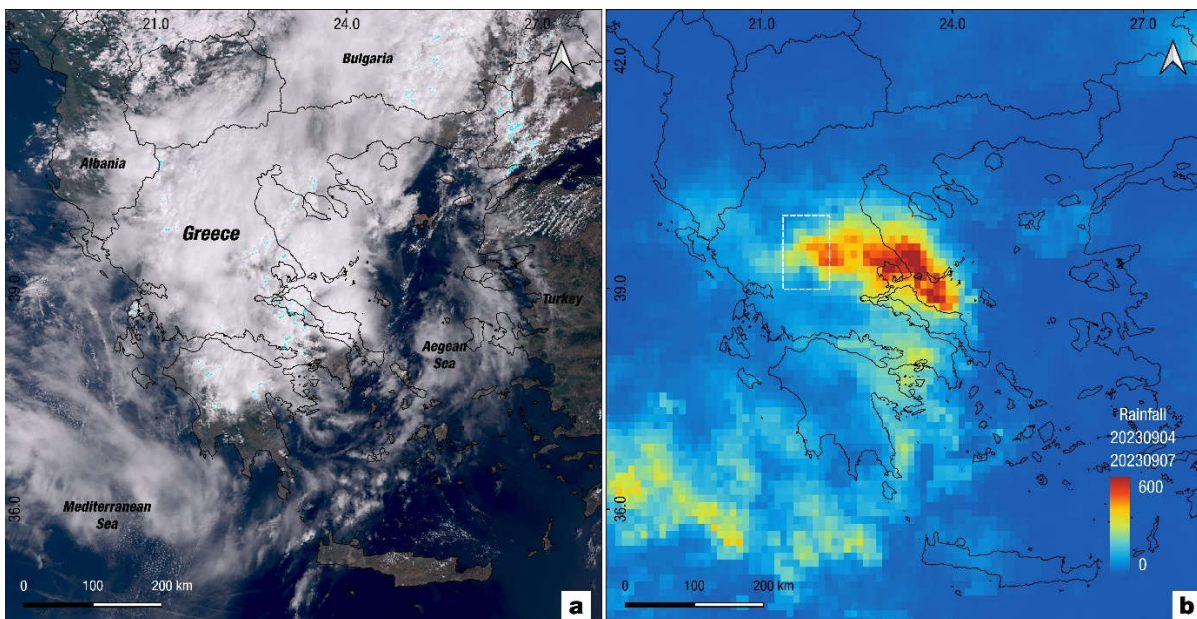
Cyclone (Medicane) Daniel was a devastating Mediterranean tropical-like cyclone that affected Greece during September 4-8 2023. Severe rainfall in central and southern Greece led to widespread landslides and flooding that caused more than 2 billion euros in damages. Flooding in Thessaly region surpassed 1 million hectares, the largest recorded flood event in recent history. The areas most affected by landslides and debris flows was Pilio mountain range along the Aegean coast and the mountainous part of Western Thessaly, along Pindos Mountain range, where severe mass wasting was also documented during Medicane Ianos in September 2020. Using post-event satellite imagery (WorldView, Planet and Copernicus Sentinel-2), and field surveys a detailed inventory of more than 3,000 landslides was recorded within an area of 2,7000 km<sup>2</sup> in the mountainous part of Western Thessaly. Numerous damaging debris flows and debris floods were also mapped along most of the major rivers and streams of this area. Most landslides were shallow landslides of few meters up to 20-30 meters, but also a major number of large (up to 0.2 km<sup>2</sup>) earth and rock slides were also mapped. The largest rock slide (Pirra landslide), documented in detail by a field and UAS survey, occurred at the ridgeline above Pirra settlement, Trikala region. Pirra slide created a landslide dam that blocked a small ephemeral stream and led to the creation of a small ~7,000 m<sup>2</sup> lake that persists seven months after the event. The detailed landslide inventory shows a narrow concentration that is interpreted to be related with the significant local variations of heavy rainfall, and also a strong correlation with either highly susceptible geological formations or prehistoric/inactive large/giant landslides. The Daniel landslide inventory (2023) is also compared with the inventory of Medicane Ianos (2020), as they have a similar distribution along the same area, and also have a significant overlap.

### Key words

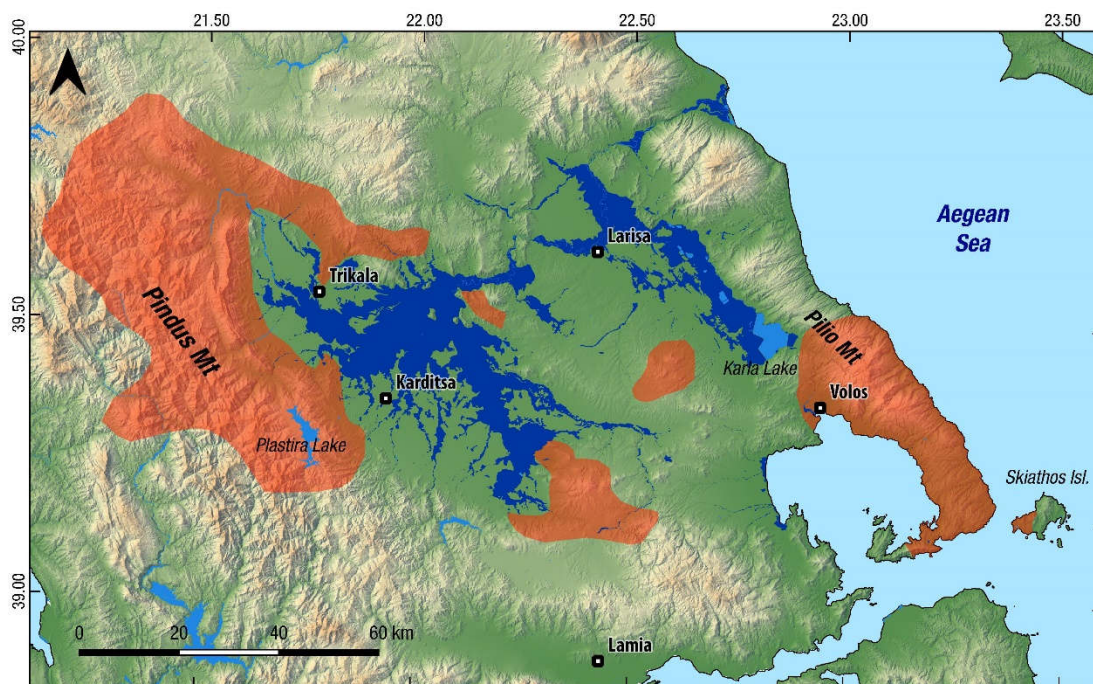
Landslides, inventory, Medicane, Daniel, remote sensing, Greece,

## 1 Introduction

Severe meteorological phenomena such as storms, hurricanes and cyclones have devastating impact on the population, infrastructure but also the natural environment. Apart from flooding, these events usually trigger numerous landslides along the impacted areas (Larsen 2008). Mapping and studying of these landslide are necessary steps towards understanding and mitigating these types of natural disasters.



**Figure 1.** a) Copernicus Sentinel-3 satellite image from Cyclone Daniel landfall, September 4 2023. b) Accumulated rainfall from satellite measurements (NASA GPM) from September 4 to September 7 2023. White dashed rectangle marks the study area in western Thessaly.



**Figure 2.** Overview of the effects of Medicane Daniel in Thessaly region. Dark blue color marks the cumulative flooded areas during and shortly after the landfall (September 2023), mapped from Landsat 8 and Sentinel-2 satellite imagery. Total flooded area exceeds 1400 square kilometers. Major landslide affected areas are marked with orange polygons, based on satellite mapping.

The Mediterranean Basin is one of the most cyclogenetic regions worldwide as a result of its characteristic morphology. Medicanes (Mediterranean hurricanes), a concatenation of Mediterranean Sea with hurricanes, resemble tropical cyclones but present certain differences like much shorter expected lifespan (Miglietta 2019).

Medicane Ianos (September 2020) was the first devastating event that led to extensive destruction in Greece, including flooding, serious damages to infrastructure and numerous landslides (Lekkas et al

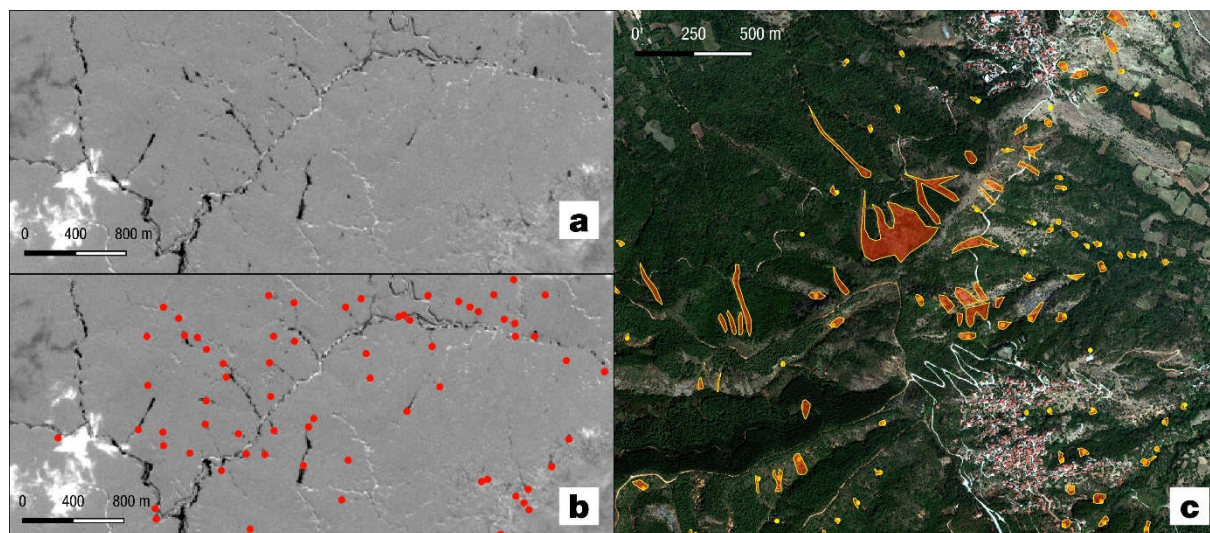
2020; Zekkos et al 2020; Lagouvardos et al 2022). A large number (>2000) of landslides were triggered by Ianos in the mountainous area of western Thessaly (Valkaniotis et al 2022). Cyclone (Medicane) Daniel, three years after Ianos, landed on Greece in September 2023. From September 4 up to September 7 2023, central Greece and especially Thessaly region, experienced severe rainfall exceeding 1000 mm at places (Figure 1). More than 1400 km<sup>2</sup> of Thessaly were flooded during this event (Figure 2). Debris flows and floods in mountainous watersheds and torrents led to serious damages of property and infrastructure in most parts of Thessaly. Southern Pilio mountain and the mountainous area of western Thessaly (Pindos mountain range) experienced thousands of landslides triggered by Cyclone Daniel (Lekkas et al 2023; Qiu et al 2023). We focused on the landslides triggered in the western Thessaly region, in order to develop an event-based landslide inventory.

## 2 Data and Methods

### 2.1 Remote sensing data

We acquired all available USGS Landsat 8/9 (15 meters ground resolution) and Copernicus Sentinel-2 (10 meters ground resolution) satellite imagery after the event, covering the dates of September 8 up to September 15 2023. Additional frames of Planet imagery (3-4 meters ground resolution) was acquired over the study area with multiple dates (September 8 – September 14). Parts of the study area were covered by early post-event very high resolution (<2 meters ground resolution) satellite imagery (WorldView-3, SPOT, GeoEye-1) that were acquired through Copernicus Data Archive.

A series of post-event field surveys in the study area (Trikala – Karditsa, Thessaly) were performed in the days following the event. During these surveys, satellite imagery rapid mapping was verified and checked in the field. In more than 15 locations, UAS photogrammetric surveys were executed in sites where major landslides occurred.

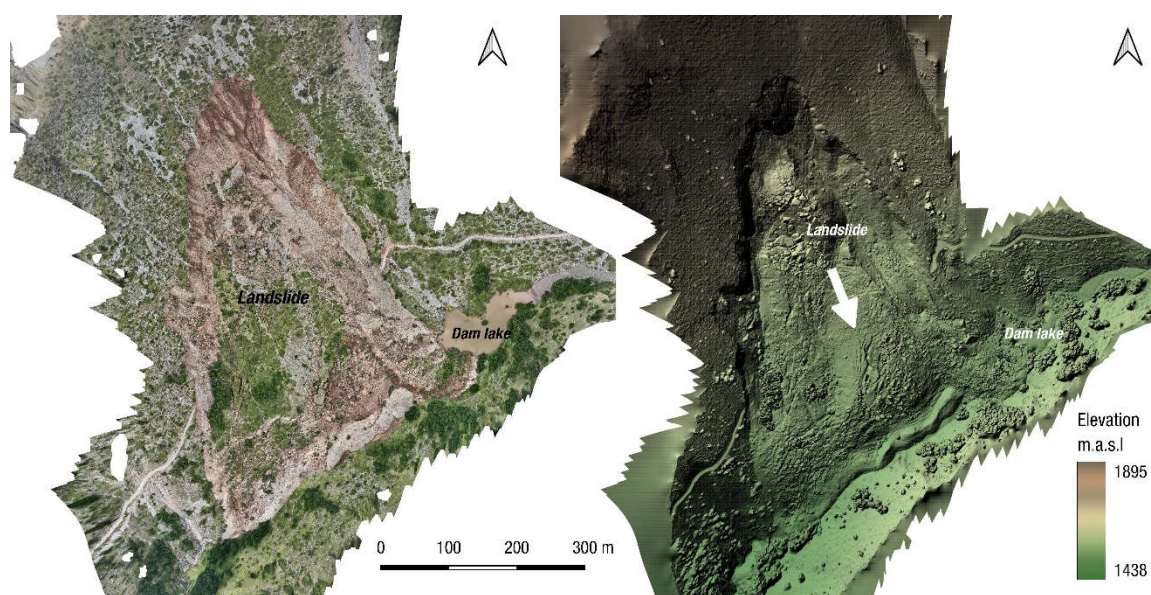


**Figure 3.** a) Example of landslide mapping using Sentinel-2 band 04 normalized difference index as an aid. Dark colors are areas that changed between the two dates and can mark the location of landslides. b) Same view with mapped landslide locations as red dots. c) Mapped landslide polygons (orange) over a WorldView-3 image (Fanari/Kanalia settlements, Karditsa).

### 2.2 Landslide inventory mapping

A preliminary landslide inventory was compiled using high resolution Copernicus Sentinel-2 multispectral imagery (Figure 3). Landslides were mapped using visual inspection, with comparison of

pre- and post-event images. Manual process was assisted by using semi-automatic methods (Valkaniotis et al 2022) such as normalized band differencing (Figure 3).



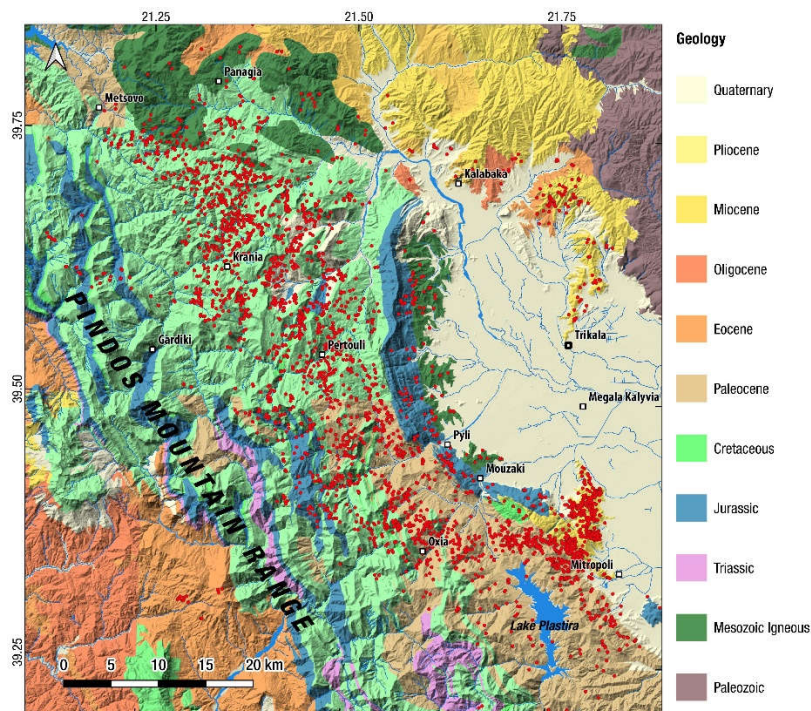
**Figure 4.** The large landslide dam that was triggered near Pirra settlement, Trikala. Orthophoto map (a) and digital surface model (b) from UAS photogrammetric post-event survey.

After the development of the preliminary rapid mapping landslide inventory, we proceeded with the final event inventory, using Planet and VHR satellite imagery for more detailed mapping of landslide locations and polygons. UAS orthophotos and digital elevation models of major deep-seated landslides were also used for detailed delineation. One of the largest landslides with length exceeding 500m was triggered at the Pindos mountain range, near Pirra settlement, Trikala region, and created a small landslide dam lake that persists up to this date (Figure 4).

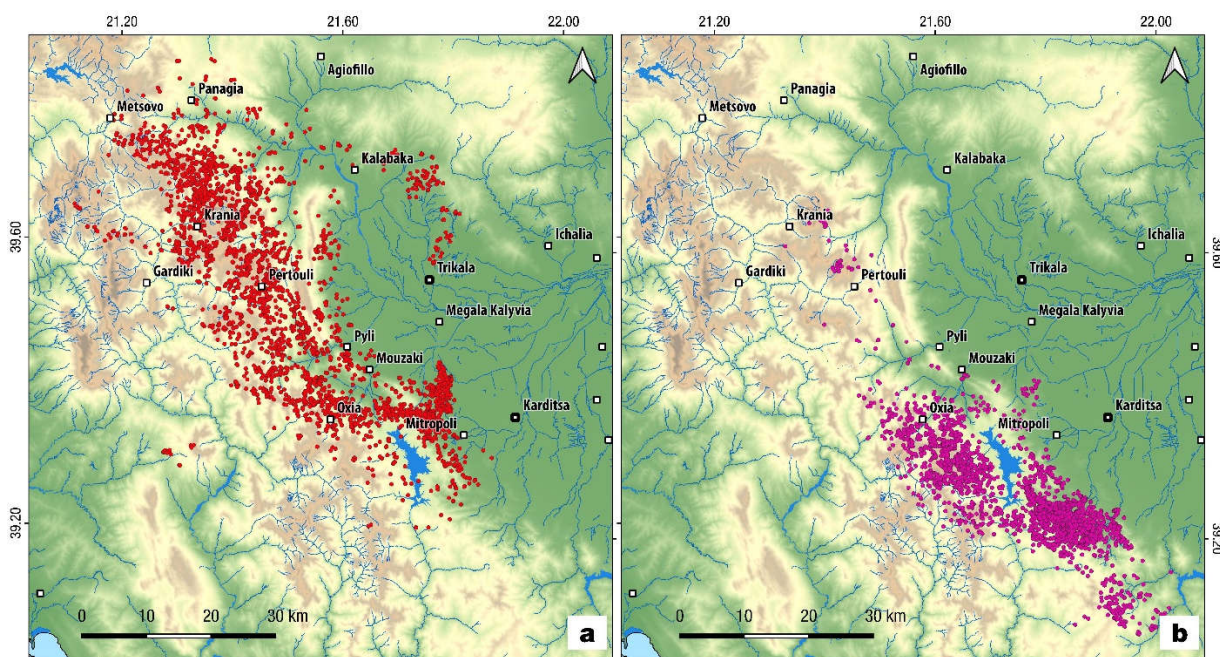
### 3 Results

The preliminary landslide inventory of 3,278 landslides is presented in Figure 5. Most of the landslides are found along the Pindos Mountain range, with additional concentrations in the hilly areas north of Trikala and near Mouzaki. A significantly increased number of landslides is expected after the completion of the detailed landslide inventory.

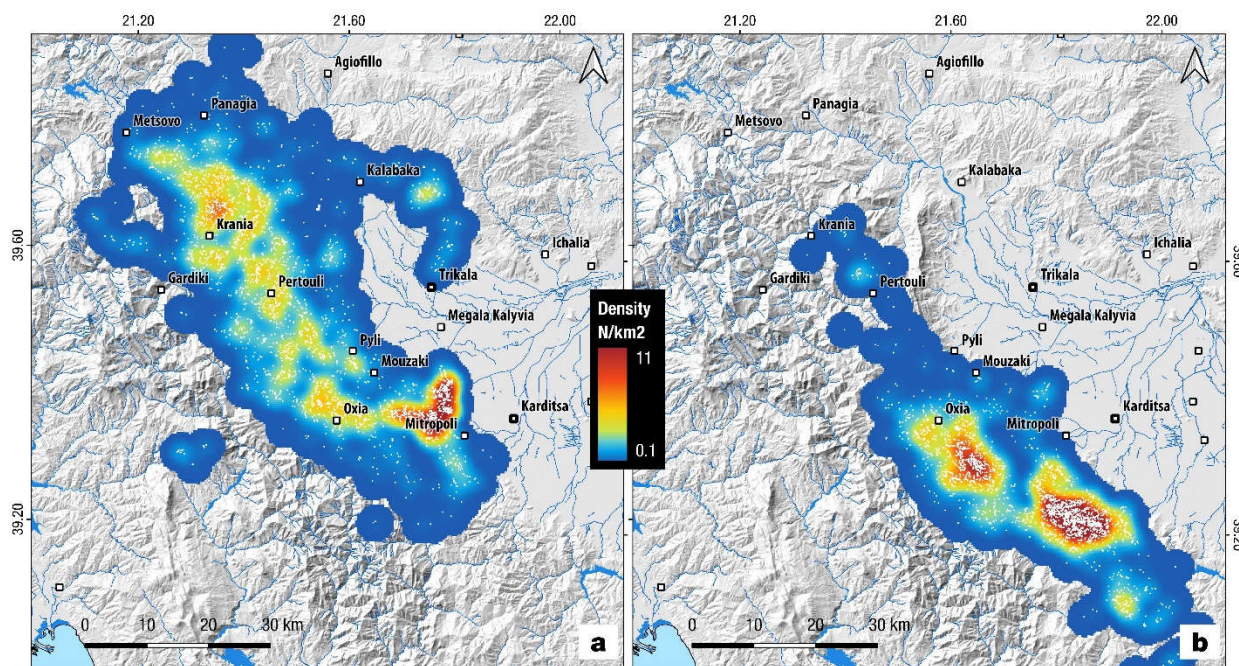
Studying the distribution of landslides, we can estimate the area of peak rainfall on the mountainous part of the affected region (Figures 5 & 6) as the one that encloses most of the landslides. A comparison with the Mediane Ianos inventory (Figures 6 & 7) shows the more severe intensity of the Daniel event, that led to more landslides in the same region but also triggered a large number of rockslides and large deep-seated landslides that were quite uncommon for the Ianos inventory. Distribution and density of landslides show a correlation with geological formations susceptible to landslides, but also with local rainfall amount and rain intensity during the three days Daniel event.



**Figure 5.** Preliminary landslide inventory (red dots). Simplified geology from Hellenic Survey of Geology & Mineral Exploration (HSGME) geological map sheets.



**Figure 6.** a) Landslides triggered by Cyclone Daniel (red dots, September 2023). b) Landslides triggered by Cyclone Ianos (purple dots, September 2020). Modified after original inventory from Valkaniotis et al. (2022).



**Figure 7.** a) Landslide density of Cyclone Daniel (September 2023). b) Landslide density of Cyclone Ianos (September 2020). Landslide locations as white dots. Modified after original inventory from Valkaniotis et al. (2022).

## 4 Conclusion

We developed a detailed landslide inventory related to Cyclone Daniel (September 2023) at the region of western Thessaly, Greece. More than 3000 landslides were mapped using remote sensing data (Copernicus Sentinel-2 and PlanetScope imagery) and also verified and enriched from a series of field surveys after the event. This area was also affected by Cyclone Ianos in September 2020 (Valkaniotis et al. 2022), that triggered ~2000 landslides with a significant areal overlap in both inventories. Even without including the numerous landslides that were simultaneously triggered by Cyclone Daniel in eastern Thessaly (Magnesia, southern Pilio Mountain range and Sporades islands), the western Thessaly inventory alone classifies this as the most severe landslide event documented in detail in modern Greece. The detailed landslide inventories developed for both Cyclones (Ianos and Daniel) are a valuable tool to study Medicanne effects in SE Europe and especially assessing future hazard from similar weather-related events in Thessaly region, Greece.

### Acknowledgements

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