environmental sciences proceedings

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Proceeding Paper

Multiple Supercell Thunderstorms on 11 August 2021 Following an Extreme Heat Wave in Greece: An Unusual Event †

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† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECAP 2023, Athens, Greece, 25–29 September 2023.

Abstract: Greece was hit by an extreme heat wave, with a significant impact on human health and natural ecosystems in the period between 28 July and 11 August 2021. After the end of this unusual warm period, a rare occasion of multiple supercell storms was observed on 11 August 2021 in northern and central Greece. The synoptic conditions indicated embedded short waves in a northwesterly flow and significant thermal instability across the regions of interest was evident. In conjunction with the strong vertical wind, shear organized convection was released. At least six long-track supercells were documented and the onset, evolution and specific characteristics of them are presented. All supercells moved from NW toward SE, accompanied by large hail, intense rainfall and destructive wind gusts, producing widespread damage along their track.

Keywords: supercells; heat wave; radar; severe convection; hail; strong vertical wind shear; Greece

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Citation: Christodoulou, M.; Sioutas, M.; Tegoulias, I. Multiple Supercell Thunderstorms on 11 August 2021 Following an Extreme Heat Wave in Greece: An Unusual Event. *Environ. Sci. Proc.* **2023**, *26*, 123. https://doi.org/10.3390/environsciproc2023026123

Academic Editors: Konstantinos Moustris and Panagiotis Nastos

Published: 29 August 2023

1. Introduction

The climate is changing in many ways due to natural processes and human activities. In recent decades, global mean temperatures have been rising steadily and scientists have high confidence that the warning trend is projected to continue [1]. Global warming is believed to contribute to increased frequency of occurrence, severity and duration of extreme events, causing many adverse impacts on humans and natural ecosystems. Scientific studies indicate that extreme weather events such as heat waves and severe storms become more frequent and intense [2].

Greece was hit by an extreme heat wave in the period between 28 July and 11 August 2021, with its main characteristics being an extended duration and extremely high temperatures. Many meteorological stations recorded 8–11 consecutive days with daily maximum temperature over 39 °C [3]. Especially, during the period of 1–5 August 2021, the highest maximum temperatures that were recorded exceeded 45 °C [4]. The August 2021 heat wave was characterized as one of the most extreme heat waves that Greece had ever experienced, comparable with the historic heat waves in 1987 and 2007 [5].

As a consequence of this climatic hazard, after this period of extremely high temperatures, severe storms including supercells (SCs) affected Greece. These thunderstorms marked the end of the period with heat wave conditions. Supercells are highly organized severe thunderstorms, characterized by the presence of one principal deep rotating updraft (mesocyclone), and are the longest-lived form of deep convection [6–8]. Supercells are extremely powerful and cause harm to living beings and property.

Although they are not very common weather phenomena, previous studies have shown that numerous supercell events have been observed in northern and central Greece, mainly during the hot season [9–12]. The catastrophic supercell that affected northern Greece on 10 July 2019 caused widespread damages in agriculture, while 7 fatalities and 120 injuries were reported in the prefecture of Chalkidiki [13].

In this case study, a rare occasion of multiple supercell thunderstorms that affected northern and central Greece on 11 August 2021 is investigated. The first purpose is the examination of the synoptic and mesoscale environment, with an emphasis on the analysis of thermodynamic and kinematic parameters, contributing to the development and organization of deep convection. The second goal is the documentation of supercell storms, presenting the onset, evolution and specific characteristics of them.

2. Data and Methods

In the present study, synoptic-scale surface and upper-level charts at various levels on 11 August 2021 were examined, while analysis of the mesoscale environment is based on soundings data. The study area is located in northern and central Greece and data from two C-band weather radars were used to examine the development, evolution, specific signatures and tracks of the storms. The radars were located at the Filyro (40.67 N, 23.01 E) and Liopraso (39.67 N, 21.85 E) sites and operated within the framework of the Greek National Hail Suppression Program (GNHSP) conducted by the Hellenic Agricultural Insurance Organization (ELGA). Radar data were recorded and processed using TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting) [14]. A full-radar-volume scan needed approximately 3.5 min, and the active radar range is 230 km. Radar analysis was complemented by satellite data from MSG.

3. Results

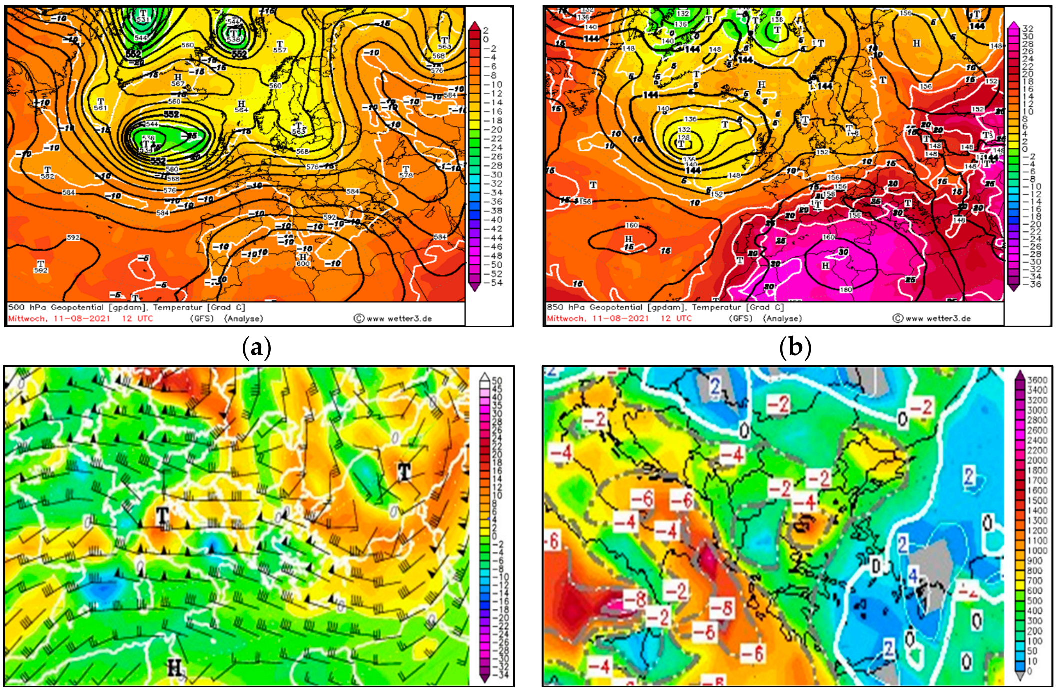
3.1. Synoptic and Mesoscale Environment

The feature of interest, on 11 August 2021, was an upper-level ridge situated over Greece at 00:00 UTC, establishing a northwesterly flow, while an extended thermal trough covered the central Mediterranean area (not shown). At 12:00, there were indications of weak embedded disturbances in this circulation, acting as a trigger mechanism for convection (Figure 1a). The heights dropped and baroclinic instability characterized the wider region. At middle levels (850 hPa), an intense thermal ridge extended from Africa to Central Europe, feeding Greece with very warm air masses on the order of 25 °C (Figure 1b). Greece has experienced high temperatures that soared above 40 °C in many regions for a long period, since the end of July. The August 2021 heat wave was extreme, and the maximum temperatures reached their record values at many meteorological stations. Coincident with that, high pressure was the dominant feature over Central and Eastern Europe (not shown).

At upper levels, the existence of the subtropical jet stream over southern Europe, as indicated in Figure 1c, was crucial. Greece was under the influence of a relatively weak jet streak, which contributed to the vertical strong wind shear. The position of the jet stream blocked the advection of the coldest air masses from the north until the next day.

The examination of the vertical profile of the atmosphere was based on representative sounding analysis using SHARPpy [15]. The 06:00 sounding of Thessaloniki revealed important potential for severe convection with a moderate MLCAPE of 1051 JKg^{-1} to a strong MUCAPE of 2744 JKg^{-1} favoring strong updrafts. A large CAPE in the layer from −20 °C to −40 °C favors rapid hail growth. The DCAPE was 1307 JKg^{-1} and it indicated the strength of the downdraft, contributing to strong wind gusts. The considerable thermal instability was reflected by high values of several instability indices (TT: 52, KI: 29, SI: −1, SWEAT: 198), while the Lifted Index produced impressive values from −5 (ML) to −10 (MU), indicative of moderate-to-extreme instability (Figure 1d at 12:00 UTC). The lapse rates from middle-to-upper layers were up to 8.0 Ckm^{-1}, suggestive of unstable conditions.

Vertical wind shear has been found to play a significant role in organizing convective storms and supercell development [16]. Between the CAPE and vertical wind shear, the second is the most crucial factor for supercell creation, as it causes the development of dynamic processes in the storm, which affect the evolution, strength, longevity and motion of the storm.



(**a**) (**b**)

(**c**) (**d**)

Figure 1. Analysis charts on 11 August 2021 at 12:00 UTC: (**a**) 500 hPa—geopotential height (gpdam) and temperature (color shading °C); (**b**) 850 hPa—geopotential height (gpdam) and temperature (color shading °C); (**c**) 300 hPa—wind speed (knots) and relative vorticity ($10^{-5}s^{-1}$); (**d**) Lifted Index (°K) and mixed-layer convective available potential energy (Jkg^{-1}). www.wetter3.de (accessed on 28 August 2023).

That day, the atmosphere indicated a strong vertical wind shear favorable of severe convection and possible development of supercells. The low-level wind shear (0–3 km) of 26 kt was moderate, while a strong deep-layer shear (0–6 km) of 43 kt and BRN shear of 34 m^2s^{-2} were best-related to supercell development. The 0–6 km shear in excess of 40 kt supports supercells, with persistent updrafts that contribute to a large hail production. An effective bulk shear (EBWS), which is designed to account for elevated and surface-based supercell environments, was 41 kt, promoting supercellular processes.

Furthermore, the compensation between instability and wind shear magnitude was high, as it was presented with a Craven Significant Severe of 23,370 m^3s^{-3}, indicating significant hail and wind. The SRH (0–3 km) of 68 m^2s^{-2} was not great, but Bunkers [17] found that either left- or right-moving supercells can occur for SRH varying from −40 to 175 m^2s^{-2}. In addition, the shape of the shear profile, as depicted in the hodograph, strongly influenced the storm evolution.

3.2. Description of the Event: Supercells Evolution

On 11 August 2021, based on the Filyro radar, the thunderstorm activity started at about 10:30 UTC in Bulgaria and at 11:28, a storm popped up and swept to Greece, where it presented supercellular characteristics (first supercell referred to as SC1). Almost one hour later, another two storms appeared simultaneously and finally evolved into SC2 and SC3 in northern and central Greece, respectively. SC3 originated more to the south compared to the other supercells and presented less intense characteristics (not shown). At 14:02, SC1 indicated maximum reflectivity of 69 dBZ, echo tops up to 16 km and impressive hail core, which is well reflected by the "Hail Mass Aloft" radar parameter that exceeds 6400 ktons (Figure 2a). At the same time, a group of cells spawned beyond Greece's northern border and swept across Greece. One of these was seeded at an early stage, in the frame of the GNHSP, and finally did not indicate supercellular features, while another cell that followed the same track about 10 km behind, evolved into SC4. A few minutes later, at 14:20, the radar detected SC5 a few kilometers behind SC2.

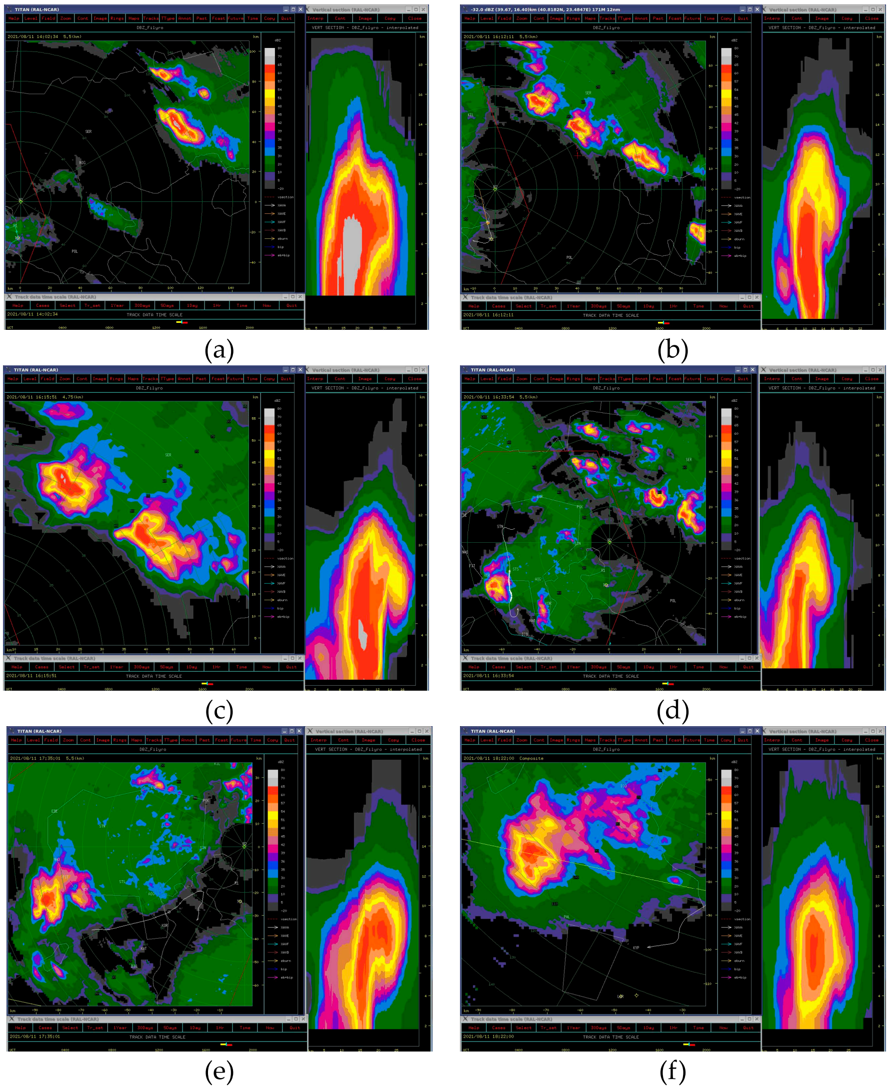


Figure 2. Radar reflectivity images and vertical cross-sections at different times and levels on August 11, 2021: (**a**) 14:02 UTC (5.5 km)—SC1; (**b**) 16:12 UTC (5.5 km)—SC2; (**c**) 16:15 UTC (4.75 km)—SC5; (**d**) 16:33 UTC (5.5 km)—SC4; (**e**) 17:35 UTC (5.5 km)—SC6; and (**f**) 18:22 UTC (composite)—SC6.

The deep-layer shear orientation, with respect to the line of forcing, defines the interactions between the neighboring storms and creates a more complicated pattern, contributing to the growth and longevity of supercells [18].

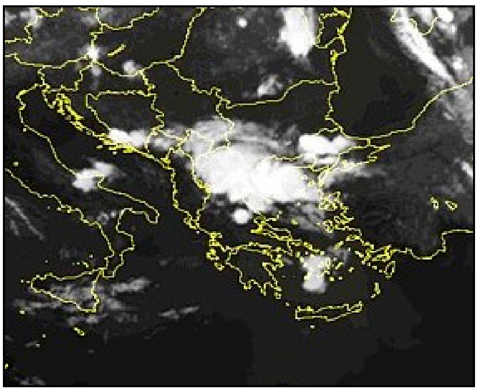
Later, at 16:04, a radar image presented both SC2 and SC5 with almost similar maximum characteristics, while at 16:12, the well-formed "Hook Echo", discrete "Bounded Weak Echo Region" (BWER), as well as the characteristic signature of the V-notch were well distinguished (Figure 2b). At 16:15, typical supercellular signatures of SC5 were observed, specifically the characteristic "vault" and BWER presented in Figure 2c, while at 16:33, the quintessential hook and forward flank notch of SC2 were impressive. During the periods of 16:08–16:16 and 16:33–16:58, cloud seeding was contacted to SC4, while the supercellular characteristics were detected just before the second period of seeding (Figure 2d). Finally, at 15:39, another storm generated in a multi-environment in a neighboring country and by the time it reached Greece, a feeder cell popped up and rapidly the storm intensified in a very powerful supercell (SC6) with impressive features (Figure 2e). SC6 was discrete and isolated, had larger dimensions than the aforementioned supercells and moved southeastward across central Greece (Figure 2f). Based on the author's data, the six identified supercells in one day set a single-day record since 2004. Some characteristics and radar parameters concerning the six supercells are presented in Table 1.

Table 1. Characteristics and radar parameters related to the six supercells (SCs) on 11 August 2021.

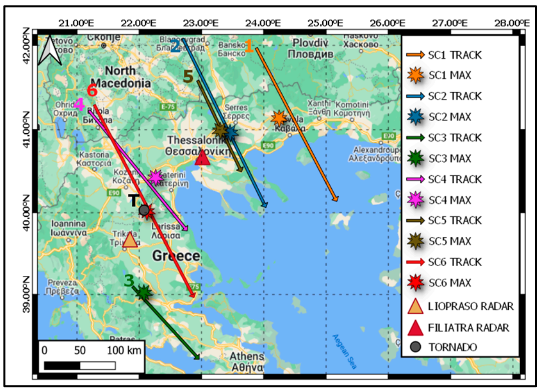
Characteristic	SC1	SC2	SC3	SC4	SC5	SC6
Lifetime (h)	5.0	6.3	2.6	4.1	3.4	4.9
Distance travelled (km)	235	252	139	213	135	292
Speed (km/h)	47.0	40.0	55.6	52.0	39.7	59.6
Zmax_Level > −5 °C (dBZ)	69	68	63	66	68	68
Echo Top max. (km)	16.0	16.0	13.0	13.5	13.5	15.0
Max. Diameter of E_{30dBZ}	54	30	20	35	24	61
Max. VIL (kgm^{-2})	213.5	243.7	101.5	127.1	220.4	140.2
Hail Mass Aloft (ktons)	6400.3	4401.7	901.7	1113.0	4069.4	3119.0
SC Char. Dur. (h) and (% lifetime)	1.0 (20.0%)	1.6 (25.4%)	0.4 (15.4%)	0.5 (12.2%)	0.8 (23.5%)	2.3 (46.9%)

During the most intense phase of the supercell storms, maximum reflectivities of 63–69 dBZ and echo tops that penetrated tropopause (9.9 km) were observed. All of them had a long lifetime, moved at the speeds of 40–60 km/h and travelled large distances. SC2 indicated the maximum lifetime of 6.3 h and VIL of 243.7 kgm^{-2}, while SC6 had the maximum speed of 60 km/h, covering the max. distance of 292 km. During their life, they presented periods with impressive supercellular features and SC6 maintained these characteristics for 2.3 h, almost half of its lifetime, causing the most severe hail damages over the Thessaly prefecture, where a tornado was also reported during the early night hours. Although the low-level shear (0–1 km) at 06:00 was weak (3 kt), it rose during the day, reaching large values of 12 kt at night. This played a determining factor in the spawning of the tornado.

The whole thunderstorm activity was well depicted in the infrared satellite images of MSG. The severe SC6 is well captured in satellite image at 18:00 (Figure 3a), close enough to its most intense phase. The supercell trajectories were computed using the Quantum Geographic Information System (Figure 3b). All supercells moved from NW toward the SE to the right of the mean wind, accompanied by large hail, intense rainfall and destructive wind gusts, producing widespread damage along their track. According to the ELGA, monetary compensations for hail damages were significant, especially in the Thessaly prefecture.



(a)



(b)

Figure 3. (**a**) Infrared satellite imagery of MSG on 11 August 2021 at 18:00 UTC. (**b**) Tracks of the six SCs. Each number indicates the SC identity. Positions of the maximum characteristics indicated by a star, and radar locations by a triangle.

4. Conclusions

Extreme events are more frequent due to global warming and heat waves, as well as supercell storms, remaining an active subject of research due to the damage and fatalities they cause worldwide. During heat wave conditions, populations and ecosystems are exposed to extremely high temperatures with serious, and sometimes adverse, impacts, such as destructive wildfires. However, severe thunderstorms, including supercells, may also occur as a result of heat waves, causing severe damages.

On 11 August 2021, an upper-level ridge extended over Greece, while later in the day, embedded short waves in the northwesterly flow brought unstable conditions over the area. A jet streak was placed over Greece, creating a strong shear environment, favoring well-organized convection. The synoptic conditions, in combination with the diurnal heating, indicated some trigger factors for convection and enhanced supercell potential.

In this study, marking the end of an intense heat wave, six long-lived supercells were documented within a 9 h period, setting a single-day record since 2004. All of them maintained high reflectivity values, exceeding 60 dBZ, for many hours and recorded mesocyclone-distinct features over some periods. The supercells moved from NW toward the SE, accompanied by severe weather phenomena. SC6 was the costliest hailstorm, travelling for almost 300 km within a region of favorable moisture and buoyancy.

Possible interactions between neighboring supercells, as well as the cloud seeding effect for hail suppression in supercells remain interesting subjects for future research.

Author Contributions: Conceptualization, M.C.; methodology, M.C.; data curation, M.C. and I.T.; writing—original draft preparation, M.C.; writing—review and editing, M.C., M.S. and I.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request from ELGA at https://www.elga.gr (accessed on 28 August 2023).

Acknowledgments: The authors wish to thank the ELGA for meteorological and radar data.

Conflicts of Interest: The authors declare no conflict of interest.

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