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Analysis of the Extreme Weather Event "Athina" in Early October 2021 †

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Abstract: Extreme weather events are identified as a major area of interest, and further consideration is demanded. This study investigates the synoptic and dynamic aspects of a storm system, named "Athina", that affected most of Greece in early October 2021. This system is synoptically attributed to a low surface pressure generated in the Gulf of Genoa, linked to a mid-tropospheric, almost neutral tilted trough, over central Europe. "Athina" brought heavy rain and strong winds to many parts of Greece, causing flooding and landslides in several areas and caused travel disruptions, with ferries and flights cancelled due to the adverse weather conditions. The worst-hit regions were the northwestern part of the country and Evia. Synoptic maps for upper and lower troposphere, observations from Hellenic National Meteorological Service's network, and satellite imagery were usedfor the analysis of this weather event. The results from a regional numerical weather prediction model are also presented.

Keywords: storm system; flood events; numerical weather prediction; COSMO model; hindcast

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1. Introduction

The storm system "Athina" [1], the first system to be officially named under the European Meteorological Network (EUMETNET) from a nominal list provided by the meteorological services of Greece, Israel, and Cyprus [2,3] (named "Christian" by the Free University of Berlin [4]), caused a significant weather impact on many parts of Greece from 6 to 12 October 2021. An additional hazardous feature of the system was that it was reinforced in two waves. The northwestern part of the country and Evia were the regions that were hit the worst. Heavy rain, strong winds, and thunderstorms resulted in significant damage to these areas such as flooding, landslides, falling trees, power outages, and travel disruptions. Heavy precipitation occurred, such as at Corfu airport, where 168 mm of precipitation was recorded in a time period of 24 h. Severe weather lashed northern Evia as nearly 100 residents, trapped by the floods, were evacuated by local authorities, many landslides and mudslides (debris flow) were reported across several districts as a result of recently burned areas in the region; and serious damage to property and infrastructure was caused. It is worth mentioning that on Sunday,10 October 2021, the Operation Center of the Fire Department received 165 calls in only a 16.5 h period. The Civil Protection declared a "state of emergency" in some communities and municipalities in West Greece, Thessaly, and Evia due to damages caused by the stormy weather on 6–11 October. The Hellenic National Meteorological Service (HNMS) had issued a red emergency bulletin of dangerous weather phenomena on Wednesday, the 6th of October 2021 and an orange one on the 9th of October. Civil protection sent alert messages, via emergency line <112>, to the residents in several regions, citing "dangerous weather phenomena" due to the storm, warning them to limit traveling and to follow authorities' instructions. In the present work, a description of the synoptic situation of this complex system will be presented based on a

selected analysis (500 hPa, PMSL) and lightning charts. The complexities of the situation will also be addressed based on the 24-h accumulated precipitation estimated using the latest version of Cosmo regional numerical weather prediction model and in reference to the observations.

2. Data and Methodology

2.1. Synoptic Analysis

An almost neutral tilted trough, accompanied by cold-air advection in the midtroposphere, was present in central Europe on 6 October 2021, while a ridge developed over northeast Europe and broad circulation of high geopotential heights covered the Iberian Peninsula (Figure 1a).

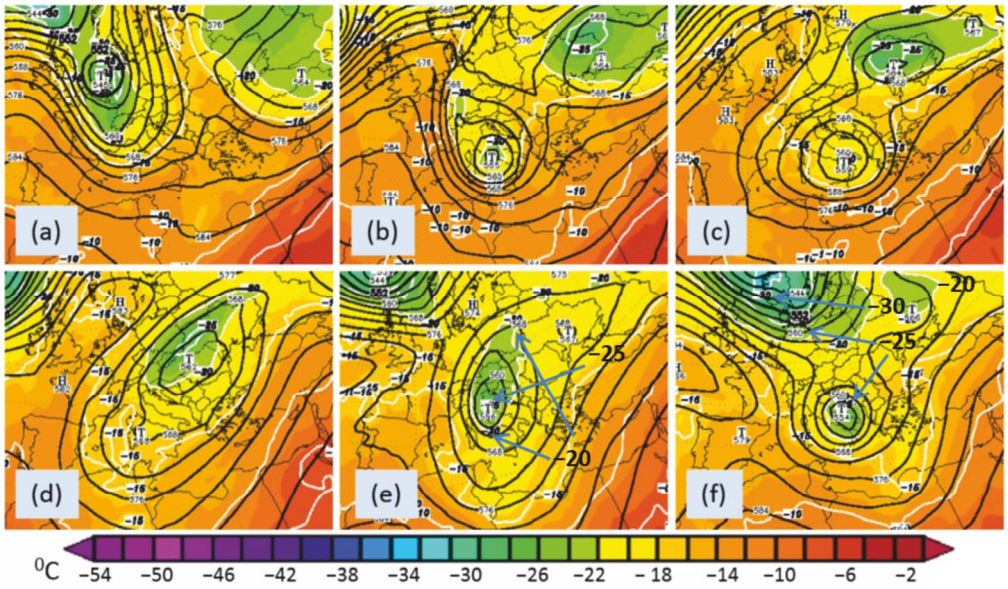

Figure 1. Geopotential height (contours, gdpm) and temperature (colored, °C) analysis (GFS) at 500 hPa at 0600 UTC for (**a**) 6, (**b**) 7, (**c**) 8, (**d**) 9, (**e**) 10, and (**f**) 11 October 2021 (© www.wetter3.de accessed on 13 May 2022).

The expansion of this anticyclonic wedge towards Scandinavia resulted in a cut-off low over Italy on next day (Figure 1b). By 8 October, cold advection from northeast fed back the system (Figure 1c) and a cut off with a second center west of Sardinia was evident (Figure 1d). The upper air low rotated counterclockwise (Figure 1e), and this setup produced the second phase of the "Athina" weather system.

The trough at the 500 hPa level led to the formation of a well-organized surface low, generated in the Gulf of Genoa (Figure 2a).The low-pressure system moved southeastward towards Greece, and the approaching cold front promoted a low-level south-southwesterly jet after midday on 6 October 2021 (Figure 2c). This meridional flow brought large amounts of moisture from the Ionian Sea towards the western parts of Greece. This factor, in association with the high instability of the troposphere (Figures 2b and 3a) and the warm sea surface temperatures (Figure 3b), produced multiple lines of thunderstorms across western regions of the country on the night of the 6th and during the day of the 7 of October (Figure 2d,f). A rather weak deepening of the cyclone that reached 1005 hPa took place at midday on 6 October 2021 and then remained almost stationary with a low value of 1000 hPa, with no significant change, over 18 h from 7 October 2021, 18 UTC, to 8 October 2021, 12 UTC. The low-pressure system then filled up, resulting in the end of the first phase of heavy and persistent precipitation to the studied area. In the second phase of "Athina", an almost stationary low 1015 hPa, without frontal activity, was present from 9 October 2021, 06 UTC, to 10 October 2021, 18 UTC, in south Italy, Sicily, and the Ionian Sea, afterwards moving slowly to the east, affecting the country for two more days.

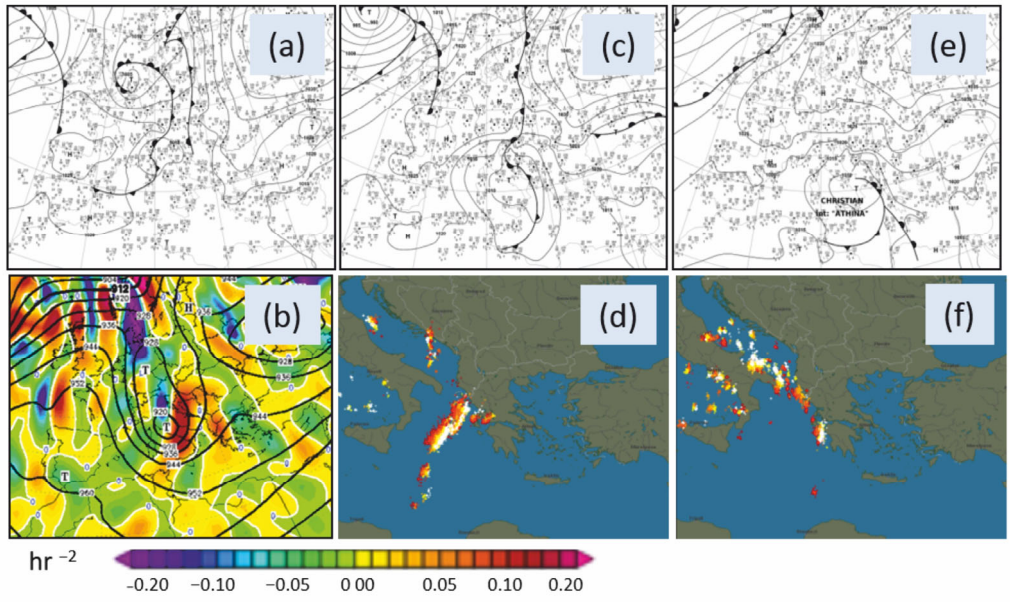

Figure 2. Surface analysis charts for PMSL at 06-10-2021/0600 UTC (**a**), 07-10-2021/0600 UTC (**c**), and 08-10-2021/0000 UTC (**e**), and 300 hPa GFS geopotential height (contours, gdpm) with absolute vorticity advection (colored, h^{-2}) at 07-10-2021/0000 UTC (**b**) (© www.wetter3.de, accessed on 13 May 2022) as well as lightnings at 7-10-2021/0600 UTC (**d**) and 8-10-2021/0000 UTC (**f**) (© www.blitzortung.org, accessed on 13 May 2022).

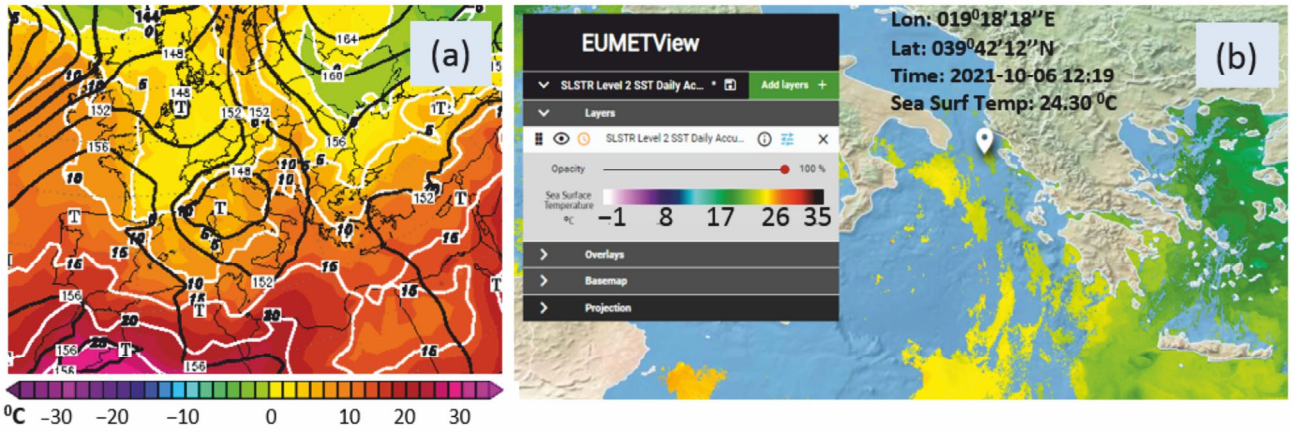

Figure 3. GFS geopotential height (contours, gdpm) and temperature (colored, °C) at 850 hPa at 6-10-2021/1800UTC (© www.wetter3.de, accessed on 13 May 2022) (**a**) and sea surface temperature at 6-10-2021/1219 UTC (© https://view.eumetsat.int, accessed on 13 May 2022) (**b**).

2.2. Cosmo Model Investigation

In order to address the development of the "Athina" storm system from the numerical weather modeling stand point, the latest version of the Cosmo model (former LM) was used [5,6]. The Cosmo model was used by the COSMO consortium (www.cosmo-$-$model.org, accessed on 13 May 2022) for operational uses, research, and development until 2022, with the ICON model [7] replacing it gradually. Nevertheless, it stands as a state-of-the-art resource for work of this type as it has provided developments of the highest standards for almost 25 years [6,8]. The model was run on a horizontal grid of 0.03° (~3.5 km) over a domain that covered the wider Mediterranean area (Figure 4a) at the new supercomputing facility of ECMWF (www.ecmwf.int/en/computing/our-facilities/supercomputer-facility, accessed on 13 May 2022). In order to minimize the forecast error, the model was run in hindcast mode and forced by the ECMWF analysis at 6hr intervals. The short-range nature of the model was addressed by the six 42hr runs, starting from 00 UTC of 6 to 11 October

2021. The 24 h accumulated precipitation starting from the 18th hr of the model runs is presented in Figure 5 along with comparisons with the SYNOP observations (Table 1) for the stations that were expected to mostly be influenced by the storm system (Figure 4b). This approach was considered as a fair compromise regarding the unveiling of the model potential to describe the exceptional complexities of this weather development that was so operationally critical.

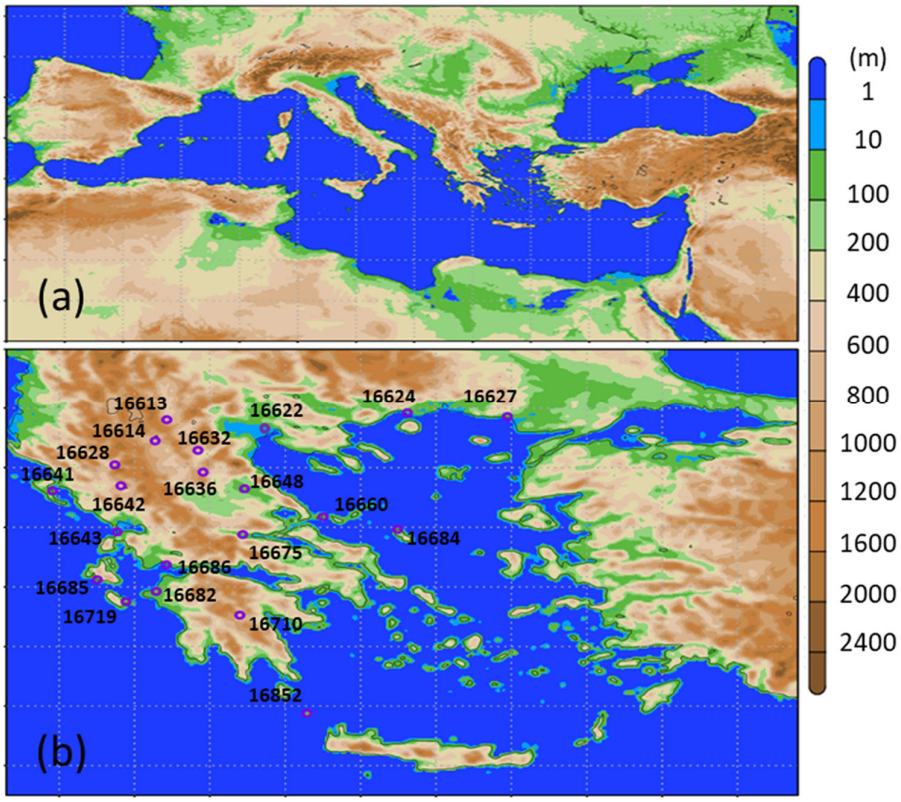

Figure 4. Integration domain of COSMO model (**a**) and the positions of the considered stations along with their designated WMO numbers (**b**).

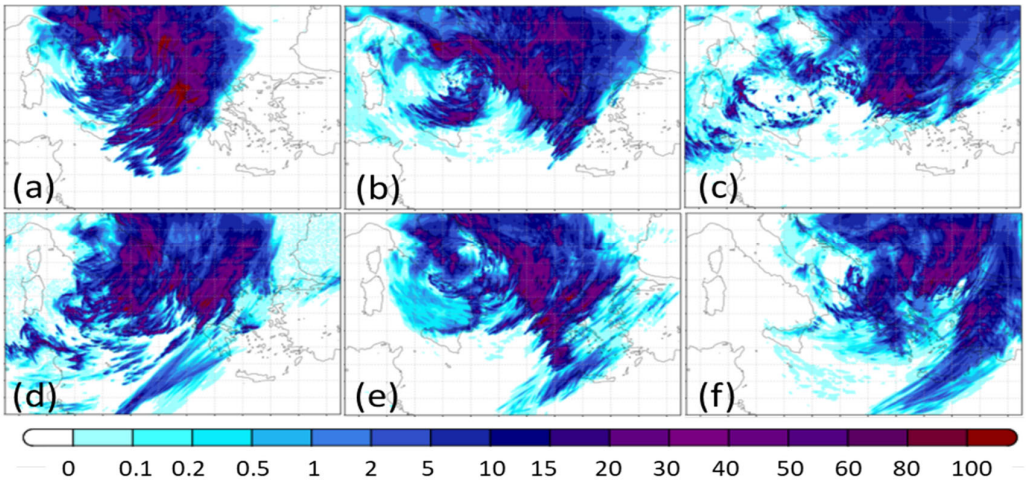

Figure 5. Accumulated 24 h precipitation, between the 42nd and the 18th hour of the hindcast cases referring to the (**a**) 7th, (**b**) 8th, (**c**) 9th, (**d**) 10th, (**e**) 11th, and (**f**) 12th of October 2021.

Table 1. List of 24 h precipitation over the examined days for the stations mentioned as most affected by the climatic bulletin of HNMS plus the station of Thessaloniki (16622). The gray-colored cells refer to the most significant observations considered. The observations start from the 18th hour of the previous day, while the model values, in parentheses, refer to the accumulated precipitation between the 42nd and the 18th hour of the hindcast cases. The orange colored cells refer to the most significant false alarms.

Station	Oct 7	Oct 8	Oct 9	Oct 10	Oct 11	Oct 12
FLOR 16613	20 (17)	49 (25)	17 (19)	21 (24)	11 (29)	3 (16)
LGKA 16614	30 (17)	32 (46)	6 (12)	8 (37)	9 (16)	30 (13)
LGTS 16622	1 (1)	3 (9)	1 (15	17 (31)	23 (14)	1 (1)
LGKV 16624	0 (0)	8 (9)	1 (15)	0 (1)	26 (4)	18 (69)
LGAL 16627	0 (0)	2 (4)	0 (17)	0 (1)	6 (19)	29 (53)
KONI 16628	56 (27)	6 (20)	14 (19)	3 (72)	11 (29)	4 (10)
LGKZ 16632	16 (12)	28 (21)	12 (12)	15 (34)	15 (10)	1 (9)
KRAN 16636	16 (7)	56 (25)	14 (32)	28 (79)	25 (3)	3 (7)
LGKR 16641	168 (64)	28 (43)	15 (44)	31 (3)	61 (3)	16 (14)
LGIO 16642	65 (42)	11 (53)	8 (18)	14 (19)	16 (38)	10 (9)
LGPZ 16643	31 (12)	22 (27)	13 (10)	4 (15)	39 (1)	21 (11)
LGLR 16648	3 (1)	45 (22)	1 (18)	10 (3)	6 (7)	3 (1)
LGSK 16660	N/A (0)	11 (7)	28 (45)	36 (0)	1 (50)	N/A (1)
LAMI 16675	35 (0)	N/A (17)	N/A (3)	16 (7)	N/A (19)	N/A (1)
LGAD 16682	8 (6)	16 (1)	9 (0)	43 (1)	31 (12)	13 (1)
LGSY 16684	0 (0)	7 (10)	1 (1)	0 (1)	26 (5)	1 (1)
LGKF 16685	35 (6)	5 (4)	0 (0)	15 (0)	62 (14)	9 (1)
MESS 16686	7 (7)	20 (38)	16 (0)	33 (1)	23 (45)	13 (9)
LGTP 16710	0 (0)	23 (1)	4 (0)	12 (1)	10 (12)	5 (5)
LGZA 16719	18 (1)	16 (1)	2 (1)	10 (1)	25 (1)	2 (3)
ANKY 16852	N/A (0)	24 (0)	N/A (0)	N/A (0)	N/A (3)	5 (0)
TOTAL/DATE	509 (220)	412 (366)	162 (278)	316 (331)	426 (312)	187 (233)

Total for all dates: 2012 (1740). N/A: Non available observation.

The extreme severity of the storm system over Greece is shown in Figure 5 in accordance with the synoptic analysis, as expected. Probably, the most important feature of these figures is the sharp differences in the distribution of the 24 h precipitation, ranging from a few mm to more than 100 mm over a relatively confined but also extensive area. It is also worth seeing that the temporal improvement in the weather in the western part of the country should have been expected to be by no means less hazardous, as it may be seen in Figure 5c, where most of Northern Greece is still seeing extreme precipitation patterns.

The complexity of the situation is further highlighted in Table 1, where the observed SYNOP values for the 24 h precipitation is compared with the model values to an accuracy of 1mm. In principle, the model values follow the observations to a good degree but from the operational standpoint, regarding the criticality of the situation, there are important differences in the extreme precipitation events both in the estimated precipitation height but also in the false alarms. An interesting point to highlight is Kerkira (LGKR), where the model evaluated considerable precipitation for the first three days (7 to 9 October) as well as the last one (12 October), but for 10 and 11 October, the comparison should be considered poor from the operational stand point. However, from the precipitation pattern and the synoptic situation, an experienced forecaster should not relax and exclude the possibility of heavy precipitation. But also, similar arguments can be placed for the "false alarm" situations like those of Konitsa (KONI) and Skiathos (LGSK) regarding 10 and 11 October, respectively.

3. Discussion and Conclusions

The severe weather system named "Athina", which affected most of Greece in early October 2021, is synoptically ascribed to a surface low-pressure, centered at 1005, generated in the Gulf of Genoa, linked to a 500 hPa circulation pattern consisting of an almost

neutral tilted-trough, over central Europe. The high instability of the troposphere, the warm sea surface temperatures of the Ionian Sea, and the abundant lower tropospheric moisture were the driving factors for the intensity and the persistence of the system that resulted in a significant impact on the region. The heavy rainfall and the strong winds caused floods, landslides, falling trees, power outages, and travel disruptions. The runs from a state-of-the-art high resolution regional numerical weather prediction model in hindcast mode supported the hazardous nature of the event, especially with respect to the extensive and continuous period of extreme precipitation events. However, the estimation of the precipitation height is not, and should not be considered a mere algorithmic output but a good support for experienced operational weather forecaster. Further investigation is in progress, along with a more systematic evaluation of the results, in order to improve the model performance. The effort is based on recent developments regarding an understanding of model sensitivity [9,10] as well as optimization of the most sensitive model parameters [11], which at present, do not display significant differences between the COSMO model and its successor ICON [10].

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The model output was stored at the ECMWF's File Storage system (ECFS) in the domain of HNMS. Due to its exceptional data volume, some arrangements regarding data availability with E.A. might be necessary in connection to the standard policies of ECMWF and HNMS.

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

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