PREDICTABILITY OF INTENSE WEATHER EVENTS OVER NORTHERN GREECE

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1. INTRODUCTION

In the framework of the project WaveForUs (http://wave4us.web.auth.gr), the Laboratory of Meteorology and Climatology (http://meteo.geo.auth.gr) of the Aristotle University of Thessaloniki (AUTH) in Greece, produces four-day operational numerical weather predictions (NWPs) for Europe, Greece and northern Greece – Thermaikos Gulf (Fig. 1b), which constitutes the target area. The NWP system is based on the nonhydrostatic Weather Research and Forecasting model with the Advanced Research dynamic solver (WRF-ARW) and resolves the latter region with a horizontal grid spacing of 1.667 km. The aim of WaveForUs project is to combine the most recent meteorological, storm surge, wave and coastal circulation models in order to produce and deliver high-resolution operational sea-state forecasts for public and emergency use in Thermaikos Gulf (Fig. 1b) in northern Greece.

The prediction of intense weather events is of primary importance to the project. An extreme precipitation event associated with lightning activity affected Thessaloniki, Chalkidiki and Thermaikos Gulf (Fig. 1b) on 15 July 2014. The strong precipitation caused significant problems, flood and damages in both infrastructure and cultivations in the city of Thessaloniki and the surrounding regions. The weather station of AUTH, which is located near the town centre, measured 98.5 mm of rain from 21:00 UTC on 14 July to 12:00 UTC on 15 July 2014. Also, the station of the Hellenic National Meteorological Service (HNMS) at the airport of Thessaloniki (LGTS) recorded 61mm of rain between 00:00 UTC and 12:00 UTC on 15 July. The comparison of these values with the climatological reports and studies of Kornaros (1999) and Anagnostopoulou and Tolika (2012) shows that the measurement of AUTH is a record maximum for all seasons, while the one of LGTS is a climatological maximum for July.

The goal of this research is to examine this intense weather event and investigate the sensitivity of its predictability to the surface conditions, aiming to improve the model performance.

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2. DATA AND METHODOLOGY

The nonhydrostatic WRF-ARW model (Version 3.5.1; Skamarock et al. 2008, Wang et al. 2013) was integrated in three 2-way telescoping nests, which covered: i) Europe, the Mediterranean sea and northern Africa (D01), ii) the central and a large part of eastern Mediterranean sea, including Greece and the Aegean sea (D02) and iii) the wider region of northern Greece - Thermaikos Gulf (D03) at horizontal grid-spacings of 15km, 5km and 1.667km, respectively (Fig. 1). In the vertical, 39 sigma levels (up to 50 hPa) with increased resolution in the boundary layer were used by all nests. The operational NCEP/GFS (National Centers for Environmental Prediction/ Global Forecast System) analyses and 3-hourly forecasts (0.5°x0.5° lat.-long.) of the 12:00 UTC cycle are employed as initial and boundary conditions of the coarse domain for the production of the 4-day forecasts. The two inner domains are initialized 6 hours after D01, in order to reduce the model spin-up. The Ferrier scheme, the Betts-Miller-Janjic scheme, the RRTMG, the Monin-Obukhov (Eta), the Mellor-Yamada-Yanjic and the NOAH Unified model represent microphysical processes, sub-grid scale convection, longwave and shortwave radiation, surface layer, boundary layer processes and soil physics, respectively.

Twelve experiments were performed in order to investigate the sensitivity of model performance to: (i) the horizontal resolution of topography (2 datasets), (ii) the land use (2 datasets) and (iii) the source/resolution of sea-surface temperatures (SSTs) as well as their temporal evolution (3 datasets/configurations). The topography was based on the United States Geological Survey (USGS) dataset (30'' x 30''; control simulation) and the very high resolution (3'' x 3'') elevation data from NASA Shuttle Radar Topography Mission (SRTM, Jarvis et al. 2008; http://srtm.csi.cgiar.org). The impact of USGS land use (30'' x 30''; control run) was compared against the one of Corine Land Cover 2000/2006 (3'' x 3''; hereafter CORN). Following Pineda et al. (2004), Corine land cover data was reclassified into USGS categories. The three SST datasets/configurations employed in the experiments were: a) the daily NCEP SSTs, with a grid-spacing of 1/12°x1/12° lat.-long., which were kept fixed throughout each simulation (control run; hereafter NCEP0). They are produced on a daily basis through the assimilation of the most recent 24-hours sea-surface observations and satellite SST measurements. b) The daily NCEP SSTs of the control run in the initial conditions, allowed to vary with time according to the WRF forecasts (hereafter NCEP1), following the model of Zeng and Beljaars (2005), and c) the daily JPL (Jet Propulsion Laboratory/ NASA) SSTs, with a grid-spacing of 0.01°x0.01° lat.-long (Chao et al. 2009), which were kept fixed throughout each simulation (hereafter NASA0). These analyses use multi-sensor satellite data and in situ observations from buoys. The experiments were performed at operational forecast mode, which implies that the boundary conditions were based on GFS forecasts and the initial SSTs were valid one day before the initial time of WRF.

Meteorological observations were available from AUTH, LGTS (about 12-13 km south of AUTH) and 27 automatic stations of the National Observatory of Athens (NOA; Fig. 1b) which are located in northern Greece. Hourly data were provided by NOA, while 3-hourly SYNOP reports were available from LGTS. The accumulated 24hourly precipitation was used from AUTH. Statistical evaluation has been performed, at the fields of mean sea-level pressure (mslp), 10m wind speed, (WS10m), 2m air temperature (T2m), 2m relative humidity (RH2m) and total 24-hourly accumulated precipitation. Lightning data were provided by the ground-based ZEUS network operated by NOA. ZEUS is a very low frequency (VLF) based lightning detection system. Detailed presentation of the system is given in Kotroni and Lagouvardos (2008) and Lagouvardos et al. (2009). The predicted lightning strikes were estimated at 5-min intervals using the methodology of Price and Rind (1992) for maritime thunderstorms. Recently, this method was successfully used along with WRF in Greece by Giannaros et al. (2015). In the present study, this methodology was employed at grid-points with predicted composite reflectivity stronger than or equal to 35 dBz. Moreover, 6-hourly gridded surface and upper-air analyses were available from the European Centre for Medium-Range Weather Forecasts (ECMWF) on a regular 0.125° latitude X 0.125° longitude grid.

The analysis was mainly performed between 39.75°N - 40.75°N and 22.5°E - 24.0°E (Fig. 1b; hereafter "area of interest"), because it encompasses Thessaloniki, Chalkidiki and Thermaikos Gulf which were strongly affected by the intense precipitation and lightning activity.

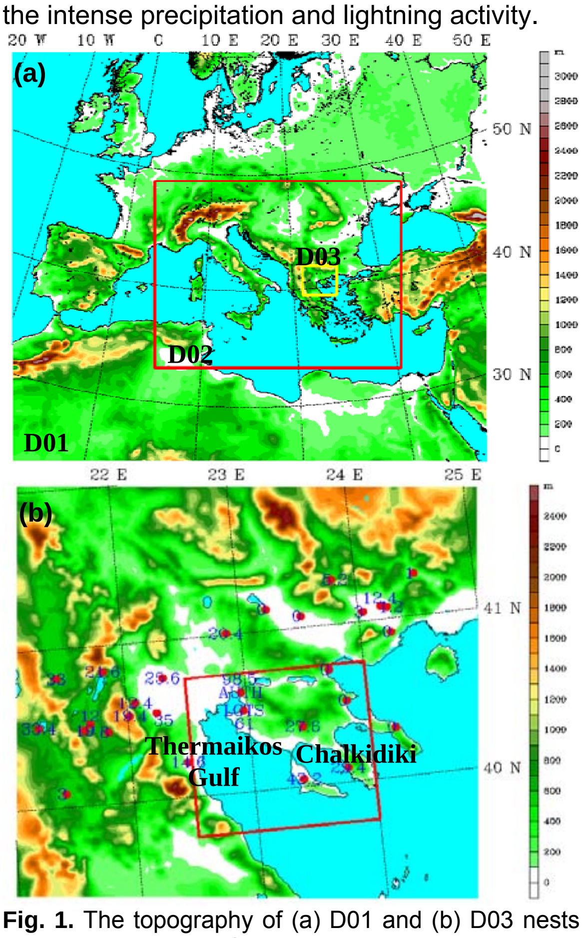

Fig. 1. The topography of (a) D01 and (b) D03 nests used by WRF-ARW. On panel (b), the red dots denote the utilized meteorological stations while the red frame encompasses the area of interest (Thessaloniki, Thermaikos Gulf and Chalkidiki). The numbers depict the observed 24hr accumulated precipitation from 18:00 UTC on 14 July to 18:00 UTC on 15 July 2014. AUTH and LGTS mark the locations of the meteorological station of Aristotle Univ of Thessaloniki and the airport of Thessaloniki, respectively.

3. RESULTS

3.1 Synoptic and mesoscale analysis

The lightning activity during the first half of 15 July 2014 in Thermaikos Gulf, Thessaloniki and Chalkidiki was characterized by two bursts. The first storms that were associated with lightning developed over the land northwest of the city of Thessaloniki and in Thermaikos Gulf between 01:00 and 01:59 UTC (Fig. 2b). During the following hours the activity extended over the whole area of interest (Fig. 2). The peaks of activity were observed between 03:00 - 03:59 UTC and 06:00-06:59 UTC, when the number of strikes in the area of interest (39.75°N-40.75°N, 22.5°E-24.0°E) rise to 288 and 341, respectively.

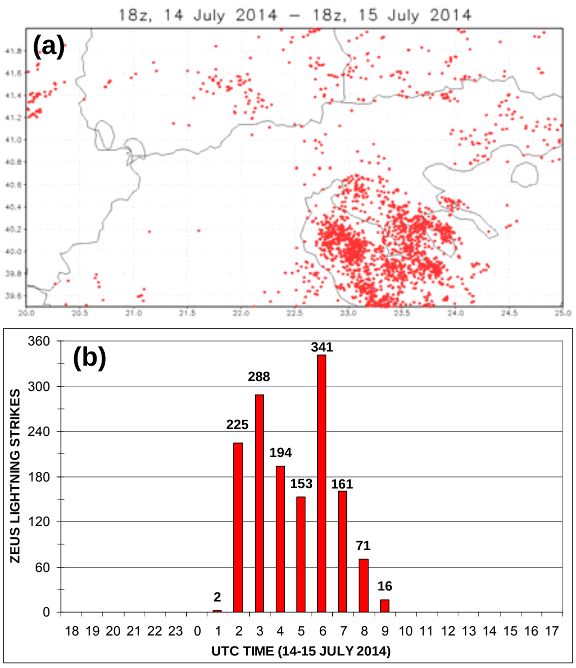

Fig. 2. a) The locations of the observed lightning strikes from 18:00 UTC 14 July to 18:00 UTC 15 July 2014, and b) timeseries of the hourly number of the observed lightning strikes in the area between 39.75°N-40.75°N and 22.5°E-24.0°E (Zeus data). In panel (b), the number of lightnings at each hour T corresponds to the period from T:00 to T:59 UTC time.

The precipitation exhibited a significant spatial variability and high amounts in northern Greece (Fig. 1b). This is a typical situation in convective events. The station of AUTH (very close to the town centre) recorded the maximum value of 98.5 mm, from 18:00 UTC on 14 July to 18:00 UTC on 15 July 2014. Large amounts were also observed at the airport of Thessaloniki – LGTS (61.0mm) and at Kassandria (42.2mm), Marmaras (29.4mm) and Polygyros (27.6mm) in western and central Chalkidiki. The amount of 98.4mm at AUTH and the whole quantity of 61.0mm at LGTS were measured between 00:00 and 12:00 UTC on 15 July.

The radiosonde ascent of the airport of Thessaloniki at 00:00 UTC on 15 July 2014 (Fig. 3), illustrated the existence of conditional instability from the surface up to 600 hPa. The convective available potential energy (CAPE) exhibited a large value (1386 J/kg) and the convective inhibition (CIN) was -61.5 J/kg. Therefore, the thermodynamic structure of the atmosphere was favorable for strong and deep convection (up to about 233 hPa). However, a mechanism was necessary in order to surpass the negative energy region and lift the air mass up to the level of free convection. Moreover, the K and Lifted index were equal to 34.1 and -3.84, respectively, suggesting a very high probability of thunderstorms (≥ 85%).

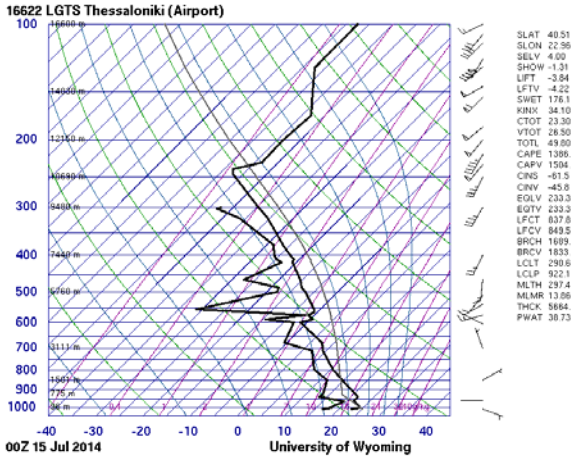

Fig. 3 Skew-T diagram at the airport of Thessaloniki (LGTS) at 00:00 UTC on 15 July 2014 (University of Wyoming).

At 500hPa, a trough was located between France and Italy at 00 UTC on 14 July 2014 and in the following hours it moved southeastward along Italy while it was transformed into a closed low. The system was located over the southern Adriatic Sea and the northern Ionian Sea at 00:00 UTC on 15 July (Fig. 4), just before the onset of the lightning activity in the area of interest and the intense precipitation in Thessaloniki. Afterwards, the center of the closed low moved over central and northern Greece and cold air masses (of about -13°C) were advected at 500 hPa over the area of interest. In the upper troposphere, the jet-stream was located south of the closed low. The area of interest was at the left flank of the jet-stream exit and the divergence at 250 hPa reached about $15{\cdot}10^{-5}$ s^{-1} at 00:00 UTC on 15 July (not shown).

At low levels, the synoptic flow induced strong convergence (locally up to about $-18{\cdot}10^{-5}$ s^{-1} at 950 hPa) over the area of interest at 00:00 UTC on 15 July. Fig. 5 shows the occurrence of both low-level convergence and upper-level divergence since the late hours of 14 July (i.e. a few hours before the triggering of the convective activity), allowing the lifting of the air masses and the development of strong vertical motions.

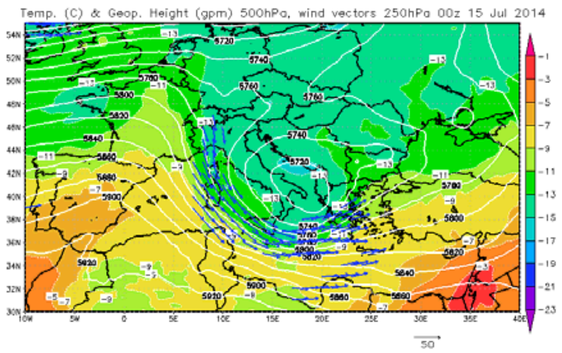

Fig. 4 Temperature (°C; shading) and geopotential height (gpm; contours) at 500 hPa and wind vectors (>30 m/s; in blue colour) at 250 hPa, at 00:00 UTC on 15 July 2014, The vector below the figure corresponds to the reference wind speed of 50 m/s (ECMWF analyses).

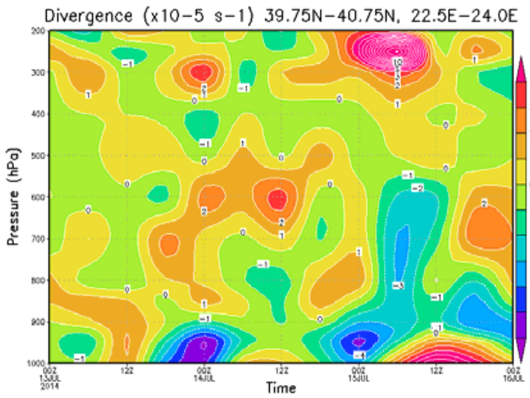

Fig. 5 Hovmoller diagram of divergence ($\times 10^{-5}$ s^{-1}) averaged in the square shown in Figure 1b (39.75°N-40.75°N, 22.5°E-24.0°E) (ECMWF analyses).

3.2 Numerical experiments

This section analyses the performance of the simulations performed by the control setup (USGS for topography, USGS for land use and fixed NCEP SSTs) and the sensitivity experiments. All the results have been calculated using the forecasts of the inner model domain (D03).

Table 1 shows the Mean Absolute Error (MAE) of mean sea-level pressure (mslp), 2m air temperature (T2m), 2m relative humidity (RH2m) and 10m wind speed (WS10m), from the inner domain (D03) of the operational runs (with the control setup) which were initialized at 12:00 UTC on 12, 13 and 14 July 2014. The errors have been calculated for the period 18:00 UTC on 14 July to 18:00 UTC on 15 July 2014. The MAEs of mslp, T2m and RH2m were calculated at the locations of the 27 NOA stations and LGTS, while the one of WS10m was estimated at LGTS. The value of the grid-point which is nearest to the location of each station was employed. It appears that the operational run of 12:00 UTC, 13 July, generally produced the most successful forecasts of the near surface variables. The MAEs of mslp, T2m, RH2m and WS10m for that run were 1.53 hPa, 1.81 K, 9.95 % and 1.8 m/s, respectively. These values are in good agreement with high-resolution model verification studies in Greece (e.g. Pytharoulis et al. 2014), also taking into account the fact that they correspond to an extreme event. Therefore, the sensitivity experiments of the surface conditions were initialised at 12:00 UTC on 13 July 2014 (i.e. about 1.5 days before the event) and were compared with the output of this control run.

Table 1. Mean Absolute Error (ME) of mean sea-level pressure (mslp), 2m air temperature (T2m), 2m relative humidity (RH2m) and 10m wind speed (WS10m) forecasts of D03 for the period 18:00 UTC on 14 July to 18:00 UTC on 15 July 2014 for different initial times. The MAE of mslp, T2m and Rh2m was calculated at the locations of the 27 NOA stations and LGTS, while the one of WS10m was derived at LGTS.

Initial time	*12UTC 12 July 2014*	*12UTC 13 July 2014*	*12UTC 14 July 2014*
mslp (hPa)	1.46	1.53	1.47
T2m (K)	2.50	1.81	2.17
RH2m (%)	14.26	9.95	12.21
WS10m (m/s)	1.97	1.80	1.91

The skill scores of mslp, T2m, RH2m and WS10m at the sensitivity experiments which were initialized at 12:00 UTC on 13 July 2014, relative to the MAEs of the control run, are displayed in Fig. 6. The name of each experiment is composed by the combination of the employed Topography_LandUse_SSTs (e.g. USGS_USGS_NCEP0 is the name of the operational control forecast). Positive values indicate that the sensitivity experiment had had a better performance than the control run. In general, the skill scores of mslp, T2m and RH2m which correspond to 28 stations ranged from about -3.4% to 3.8%. The combination of SRTM topography, Corine land use and NASA/JPL SSTs was the only one which exhibited a better forecast skill than the control forecast in all the analyzed continuous variables of mslp, T2m, RH2m and WS10m (Fig. 6). Its improvement reached 18.7% in WS10m at LGTS.

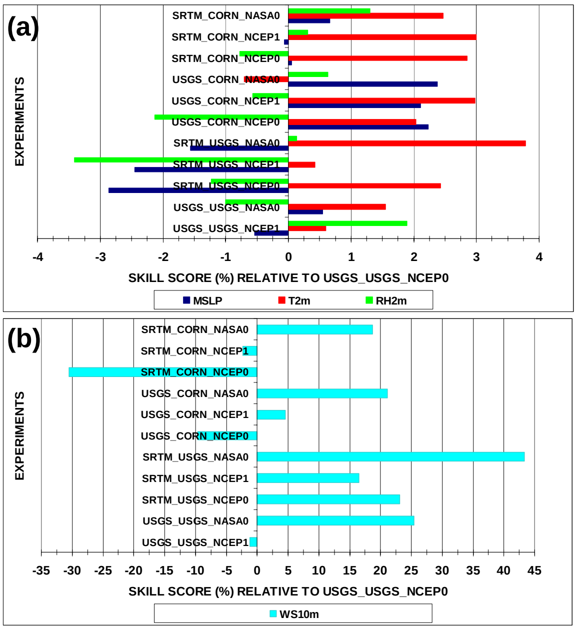

Fig. 6 The skill score (%) of the experiments relative to the MAE of the control forecast (USGS_USGS_NCEP0) in D03 for a) mean sea-level pressure, 2m air temperature and 2m relative humidity at the locations of the 27 NOA stations and LGTS, and b) 10m wind speed at LGTS, in the period from 18 UTC on 14 July to 18 UTC on 15 July 2014 (T+30 to T+54). T+0 at 12UTC on 13 July 2014.

The best categorical scores at small precipitation thresholds (>1mm in 24 hrs) were obtained by the combination of USGS topography, Corine land use and NASA/JPL SSTs (POD=0.95, FAR=0, HSS=0.91; Fig. 7a), followed by USGS_USGS_NASA0 & SRTM_USGS_NASA0. The control setup produced the 5th highest HSS (0.81), being associated with high POD (0.95) and low FAR (0.05). At higher thresholds, greater than 10mm in 24 hrs (Fig. 7b), the best scores were produced by SRTM_USGS_NASA0 (POD=0.76, FAR=0.07, HSS=0.66) and USGS_USGS_NASA0 (POD=0.82, FAR=0.13, HSS=0.65). As far as the MAE of the 24hr accumulated precipitation (from 18:00 UTC on 14 July to 18:00 UTC on 15 July 2014) at all stations in D03 is concerned (Fig. 8), the best scores appeared in USGS_CORN_NASA0 (12.1mm), USGS_USGS_NASA0 (12.9mm) and SRTM_USGS_NASA0 (12.9mm). The experiment SRTM_CORN_NASA0, which was the only one that improved the forecasts of all the continuous surface parameters relative to the control setup (Fig. 6), also exhibited a lower MAE of the 24hr precipitation and higher scores at the 10mm threshold (but not at 1mm) than the control setup. The maximum amounts were underestimated in all the experiments (not shown). For example, the control run predicted 25.17mm at AUTH and 15.16mm at LGTS. The best performance at the station of AUTH, which recorded the highest amount, was exhibited by USGS_USGS_NASA0 (25.95mm) and was followed by the control setup.

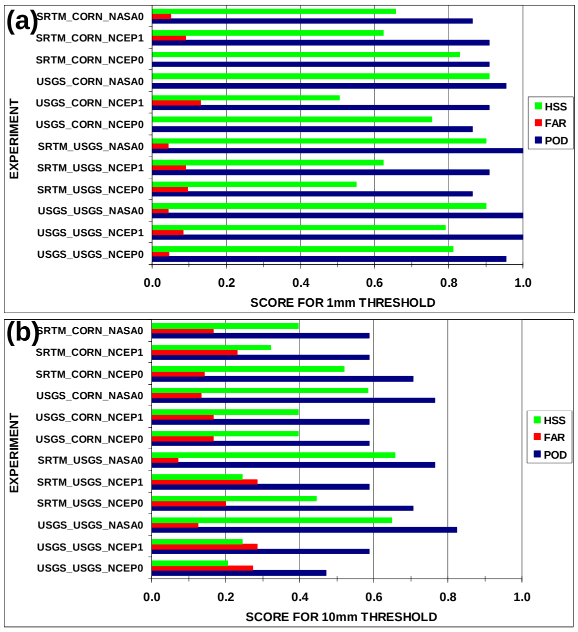

Fig. 7 Probability of Detection (POD), False Alarm Ratio (FAR) and Heidke Skill Score (HSS) of the 24hr accumulated precipitation forecasts of D03, using the thresholds of a) 1mm and b) 10mm, at all 29 stations from 18UTC 14 July to 18UTC 15 July 2014 (T+30 to T+54). T+0 at 12UTC on 13 July 2014.

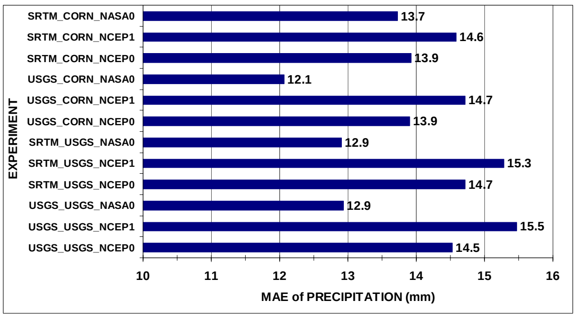

Fig. 8 Mean Absolute Error (MAE in mm) of the 24hr accumulated precipitation forecasts of D03 at all 29 stations from 18UTC 14 July to 18UTC 15 July 2014 (T+30 to T+54). T+0 at 12UTC on 13 July 2014.

The lightning threat was predicted by the operational WRF run of WaveForUs project (Fig. 9 upper left panel), which was initialized at 12:00 UTC on 13 July 2014, using the lightning parameterization of Price and Rind (1992) for marine clouds at the grid-points with predicted composite reflectivity ≥ 35 dBz. The experiments with the very high-resolution NASA/JPL SSTs provided the best representation of the spatial extent of lightning activity, because they predicted lightning strikes in the whole region of Thermaikos Gulf in agreement with the Zeus observations (Fig. 2a). Moreover, these experiments reduced the overestimated number of lightnings in the northwest subregion of D03. Further analysis is required in order to investigate whether the NASA0 runs also produced the best temporal evolution of lightning activity.

4. SUMMARY-CONCLUSIONS

An extreme precipitation event associated with lightning activity affected Thessaloniki, Chalkidiki and Thermaikos Gulf in northern Greece on 15 July 2014. The station of AUTH, which is located near the centre of Thessaloniki, measured 98.5 mm of rain in 15 hours. Also, the station of the airport of Thessaloniki recorded 61mm of rain in 12 hours. The measurement of AUTH set a new record maximum for all seasons at this station. The event took place under the influence of strong synoptic forcing associated with a mid-tropospheric closed low and strong low-level convergence. The phenomena were predicted by the operational

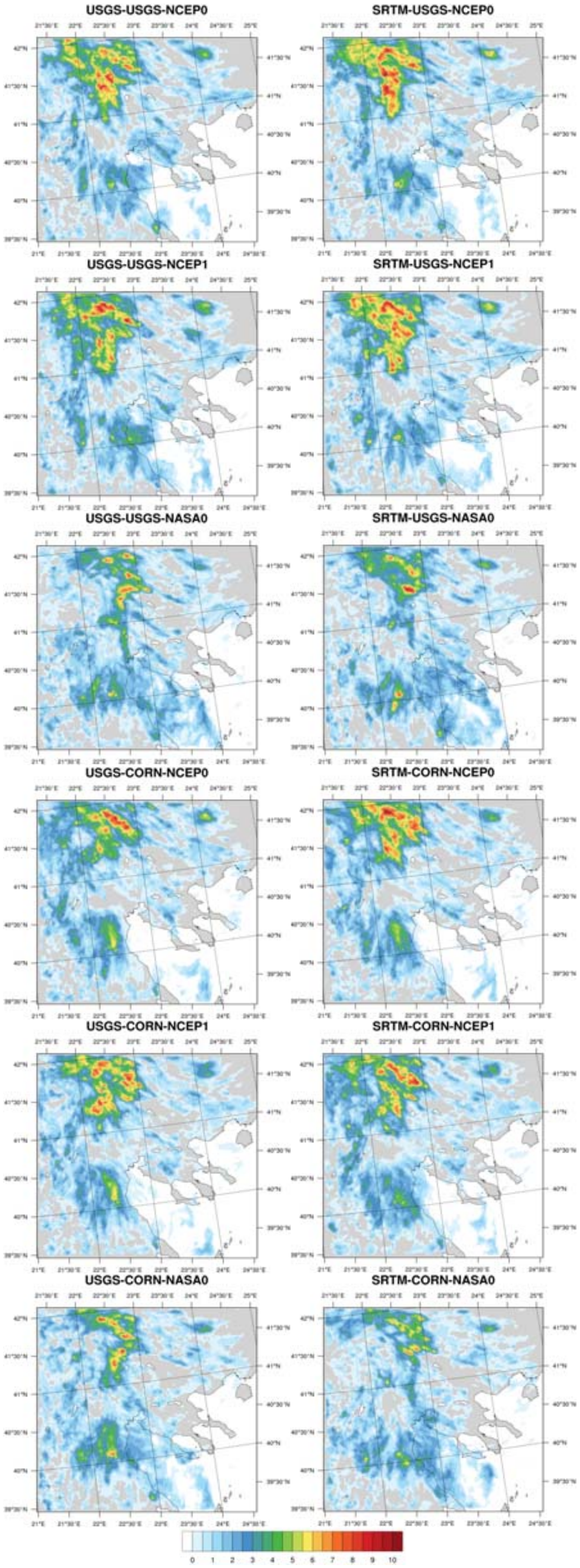

Fig. 9 The predicted number of lightning strikes from 18:00 UTC 14 July to 18:00 UTC 15 July 2014, at the various experiments, using the WRF-D03 output and the lightning parameterization of Price and Rind (1992). T+0 at 12:00 UTC on 13 July 2014.

nonhydrostatic WRF NWP model, which is utilized by WaveForUs project, along with the lightning parameterization of Price and Rind using high resolution (1.667km x 1.667km). The model results were in good agreement with the available surface observations, although they underestimated the maximum precipitation amounts at AUTH and LGTS. The use of SRTM topography, Corine land use and NASA/JPL SSTs appeared to improve the forecast skill of the control forecast in all the analyzed continuous variables of mslp, T2m, RH2m and WS10m. The best scores of precipitation and the best representation of the spatial extent of lightning activity were produced by the experiments with the NASA/JPL SSTs. This is likely to be due to changes in the sea surface fluxes, since the NASA/JPL SSTs were generally warmer than the NCEP ones up to 1.5-2K in D03, with a mean value of 0.7K. Further experiments are necessary in order to be able to generalize the above results.

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6. ACKNOWLEDGMENTS

This research work of WaveForUs project (11SYN_9_975) is co-funded by the European Union (European Regional Development Fund) and Greek national funds, through the action "COOPERATION 2011: Partnerships of Production and Research Institutions in Focused Research and Technology Sectors" in the framework of the Operational Programme

"Competitiveness and Entrepreneurship" and Regions in Transition (OPC II, NSRF 2007-2013).

The observed lightning data were provided by the ground-based ZEUS network operated by the National Observatory of Athens. ZEUS is a very low frequency (VLF) based lightning detection system. Detailed presentation of the system is given in Kotroni and Lagouvardos (2008) and Lagouvardos et al. (2009). We would also like to thank the Hellenic National Meteorological Service, the National Observatory of Athens, NCEP, ECMWF, NASA/JPL for making available the surface observations, the gridded analyses/forecasts and the SSTs, the University of Wyoming for providing the radiosonde data, NCAR for the WRF numerical model as well as USGS for the topography and land use data and CGIAR-CSI for the SRTM digital elevation data.