ΜΕΛΕΤΗ ΕΝΟΣ ΕΠΕΙΣΟΔΙΟΥ ΑΣΤΡΑΠΩΝ-ΚΕΡΑΥΝΩΝ ΜΕ ΤΗ ΒΟΗΘΕΙΑ ΥΨΗΛΗΣ ΑΝΑΛΥΣΗΣ ΠΡΟΣΟΜΟΙΩΣΕΩΝ

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Περίληψη
Κατά τη διάρκεια της 17ης και 18ης Ιουνίου 2009 η Θεσσαλονίκη και αρκετές περιοχές της Κεντρικής Μακεδονίας επηρεάστηκαν από εντυπωσιακή δραστηριότητα κεραυνών-αστραπών η οποία χαρακτηρίστηκε από δύο επιμέρους επεισόδια και αξιοσημείωτη χωρική μεταβλητότητα του υετού. Η συνοπτική κυκλοφορία έπαιξε σημαντικό ρόλο στην εμφάνιση διαφορικής μεταφοράς ισοδύναμης δυναμικής θερμοκρασίας στα κατώτερα επίπεδα και στη μέση τροπόσφαιρα. Η δυναμική αστάθεια που δημιουργήθηκε από αυτή τη διαφορική μεταφορά μαζί με τη σύγκλιση στα κατώτερα επίπεδα εμφανίζονται να είναι υπεύθυνοι για την καταιγιδοφόρο δράση. Υψηλής ανάλυσης πειράματα ευαισθησίας με το περιοχικό μη-υδροστατικό ατμοσφαιρικό αριθμητικό μοντέλο WRF-ARW, σε συνδυασμό με το δείκτη δυναμικού αστραπών-κεραυνών, έδειξε ότι οι παραμετροποιήσεις της μικροφυσικής των Goddard, WDM6 και Milbrandt-Yau έδωσαν την καλύτερη αναπαράσταση της δραστηριότητας κεραυνών-αστραπών.

STUDY OF LIGHTNING ACTIVITY WITH THE USE OF HIGH-RESOLUTION SIMULATIONS

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Abstract
During 17-18 June 2009 the city of Thessaloniki and several regions of central Makedonia were affected by impressive cloud-to-ground and intracloud lightnings associated with convective storms. This activity was characterized by two bursts and noticeable spatial variability of precipitation in Thessaloniki. The synoptic scale environment appeared to play an important role in promoting differential θ_e advection at low-levels and in the mid-troposphere. Potential instability that resulted from the differential θ_e advection together with low-level convergence are suggested to be responsible for the convective storms. High-resolution sensitivity experiments of the regional non-hydrostatic atmospheric numerical model WRF-ARW, combined with the Lightning Potential Index, showed that the microphysical parameterizations of Goddard, WDM6 and Milbrandt-Yau provided the best representations of the lightning activity.

Λέξεις κλειδιά: αστραπή, κεραυνός, αριθμητικό μοντέλο WRF, παραμετροποιήσεις μικροφυσικής, δείκτης δυναμικού κεραυνών-αστραπών
Keywords: lightning, WRF numerical model, microphysical parameterizations, LPI

1. Introduction

Lightning, which is associated with convective storms, is among the most damaging and deadly weather hazards worldwide. Despite the importance of its forecasting, the state-of-the-art atmospheric numerical models do not contain cloud electrification schemes to produce quantitative estimates of lightning threat within storms. During the last years it has been attempted to parameterize the probability, density and areal extent of lightning activity using gridded output from high-resolution sophisticated numerical models.

The lightning activity over Greece and its relationship with rainfall, topographic features and cloud microphysical parameters has been studied through climatological or case study approaches (Katsanos 2007; Kotroni and Lagouvardos 2008; Katsanos et al. 2009; Roupa 2009). It has also been achieved to utilize lightning measurements in Numerical Weather Prediction (NWP) models in order to improve convective precipitation forecasts in the Mediterranean (Papadopoulos et al. 2005). Recently, Yair et al. (2010) introduced the Lightning Potential Index (LPI) in order to predict the potential for lightning activity. They demonstrated its successful use and its superiority relative to other indices through selected case studies in the Mediterranean sea basin, including Greece.

During 17-18 June 2009 the city of Thessaloniki and several regions of central Makedonia were affected by impressive cloud-to-ground and intracloud lightning activity associated with convective storms (Figure 1). A black-out of about one hour occurred in Thessaloniki in the night of 17 June because of lightning strikes on the station of the public power corporation at Oreokastro (~10km far from the centre of Thessaloniki). The prefectures of Chalkidiki, Serres and Kilkis were similarly affected by the damages on the electrical power station.

The aims of this research that focuses on Central Makedonia are:

- to study the synoptic and mesoscale conditions that promoted the convective activity of this event
- to investigate the performance of a state-of-the-art cloud-resolving NWP model to simulate the lightning activity of this event through LPI under different microphysical parameterizations.

Figure 1: Photograph of a cloud-to-ground lightning strike at Thessaloniki on 17 June 2009.

2. Data and numerical model

Surface and upper-air observations from the airport of Thessaloniki (LGTS) and the meteorological station of the Department of Meteorology-Climatology of the Aristotle University of Thessaloniki (AUTH) were used in this study. The lightning data were extracted from the ZEUS European long-range lightning network (Lagouvardos et al. 2009) and were provided by the National Observatory of Athens. The observations were combined with the gridded surface and upper-air analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). The analyses were disseminated at 6-hourly intervals on a 0.25° lat. x 0.25° lon. A-type grid. The necessary fields were retrieved at and near the surface and on the pressure levels of 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70 and 50 hPa.

The nonhydrostatic Weather Research and Forecasting model with the Advanced Research dynamic solver (WRF-ARW Version 3.2.0) was utilized in the numerical experiments. It is a flexible, state-of-the-art numerical weather prediction system designed to operate in both research and operational mode (Skamarock et al., 2008; Wang et al., 2010). It is suitable for a broad spectrum of applications such as idealized simulations, parameterization research, data assimilation research and real-time forecasting in global and regional scales.

Two interactive model domains (Figure 2) covered Balkans and the wider area of Makedonia at horizontal grid-spacings of 10km x 10km and 2km x 2km, respectively, utilizing the staggered Arakawa C grid. Fine-resolution data (30’’ x 30’’) were used in the definition of topography, land use and soil type. Six-hourly ECMWF analyses were used as lateral boundary conditions for the coarse domain, while the fine inner domain was two-way nested to the larger one. The sea-surface temperatures were also derived from the ECMWF analysis and were kept fixed to their initial values throughout the simulations. In the vertical, 51 sigma levels (up to 50 hPa) were used by both nests. The GFDL scheme, the Monin-Obukhov (Eta), the Mellor-Yamada-Janjic level 2.5 (MYJ) and the NOAH Unified model were used in both nests to represent longwave/shortwave radiation, surface layer, boundary layer and soil physics, respectively. The terrain slope was taken into account in the calculation of the surface solar radiation flux. Cumulus convection was parameterized only in the coarse nest by the Kain-Fritsch (new Eta) scheme. The 8 microphysical schemes that were used in the sensitivity experiments are: i) Lin, ii) WRF Single Moment 6-classes (WSM6), iii) Goddard, iv) New Thompson V3.1, v) Milbrandt-Yau, vi) Morrison, vii) WRF Double Moment 6-classes (WDM6) and viii) Old Thompson V3.1. Detailed information and references can be found in Skamarock et al. (2008) and Wang et al. (2010).

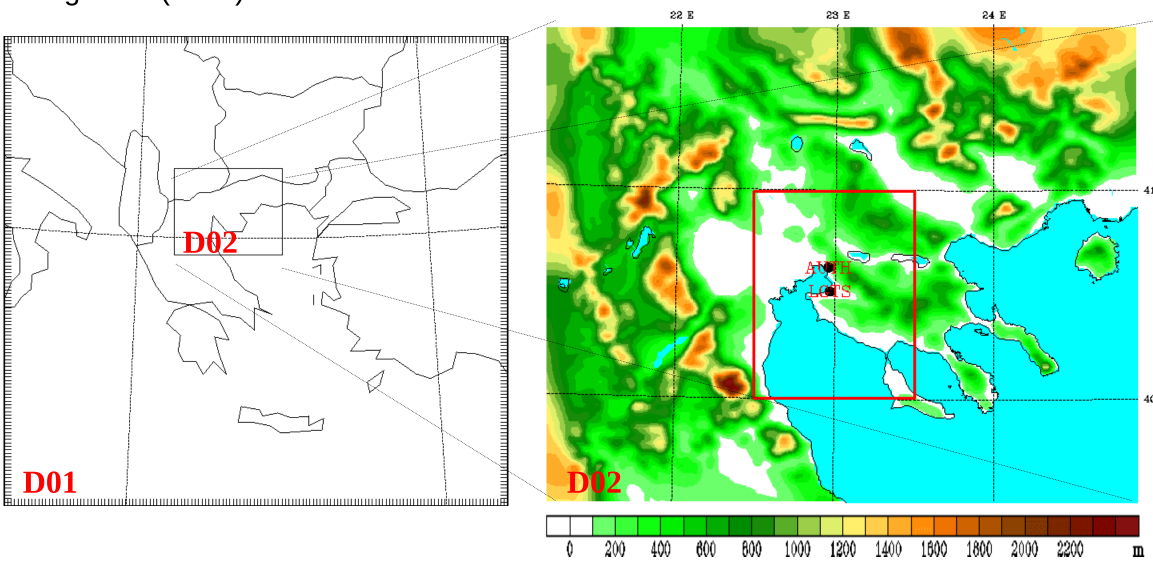


Figure 2. (a) The two nests used by WRF-ARW in the numerical experiments. (b) The topography of the inner domain (D02) and the locations of the available stations. In panel (b) the red square (40°N-41°N, 22.5°E-23.5°E*) indicates the region that various parameters were processed in Figures 3d, 5-8.*

3. Synoptic-mesoscale analysis

The lightning activity in the night of 17-18 June 2009 at Thessaloniki was characterized by two bursts. Figure 3d shows the number of lightning strikes in a square of 1°x1° centered approximately at Thessaloniki and covering the region between 40°N-41°N, 22.5°E-23.5°E (Figure 2b; hereafter referred to as area of interest). It is suggested that the number of strikes in this square represents the lightning threat in the wider area of Thessaloniki, allowing for the location error of Zeus as well. The primary burst started between 1700-1800 UTC in the plains of Imathia-Pella with the formation of cumulonimbus and affected the wider area of Thessaloniki until about 2100 UTC (Figures 3a-c). By that time a convective complex had covered the prefectures of Thessaloniki and Chalkidiki. The lightning strikes in the power station of Oreokastro and the black-out in the city of Thessaloniki occurred during this period. The maximum hourly number of lightnings in the area of interest reached 354 strikes. A second burst occurred after 0000 UTC on 18/06/09 (Figure 3d), but its hourly number of strikes did not exceed the value of 45 in the area of interest. The precipitation exhibited important spatial variability since 4.0 and 14.7 mm were observed in the airport of Thessaloniki and AUTH (located near the town centre) respectively, between 1800 UTC on 17/06/09 and 0600 UTC on 18/06/09.

The low-level atmospheric conditions in the airport of Thessaloniki (40.516°N, 22.966°E) appear in figure 4a. The temperature and dew point temperature (humidity) were almost similar during the two days before the event. However, both the temperature and the dew-point increased on 17 June. As a result, higher values of equivalent potential temperature (θ_e) were observed on that day. Maximum θ_e values of 341-342K were measured in the late afternoon and night hours (Figure 4a).

The sounding of 1200 UTC, 17/06/09 at Thessaloniki (Figure 4b) showed that the atmosphere was conditionally unstable up to about 550 hPa, while its temperature followed the moist adiabat above this level. The Convective Available Potential Energy (CAPE) was extremely small (~6 J/kg) while the Convective Inhibition (CIN) exhibited a very large value (-517 J/kg). These conditions were certainly not conducive to lifting an air parcel and trigger convection not only because a large amount of energy should be provided in order to be raised to the level of free convection (LFC) but also due to the absence of CAPE above LFC.

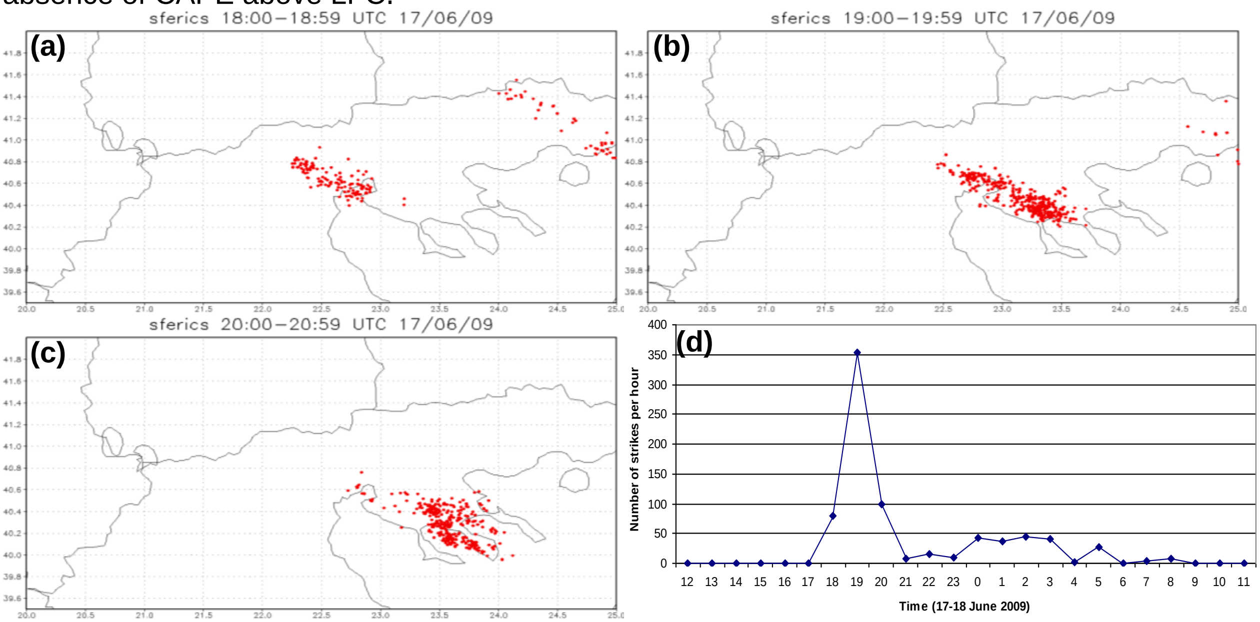


Figure 3: (a, b, c) Locations of lightning strikes. (d) Timeseries of the hourly number of strikes between 40°N-41°N, 22.5°E-23.5°E. In panel (d) the number of strikes corresponds to the time interval from T+0 mins to T+59 mins (time in UTC). Zeus lightning data.

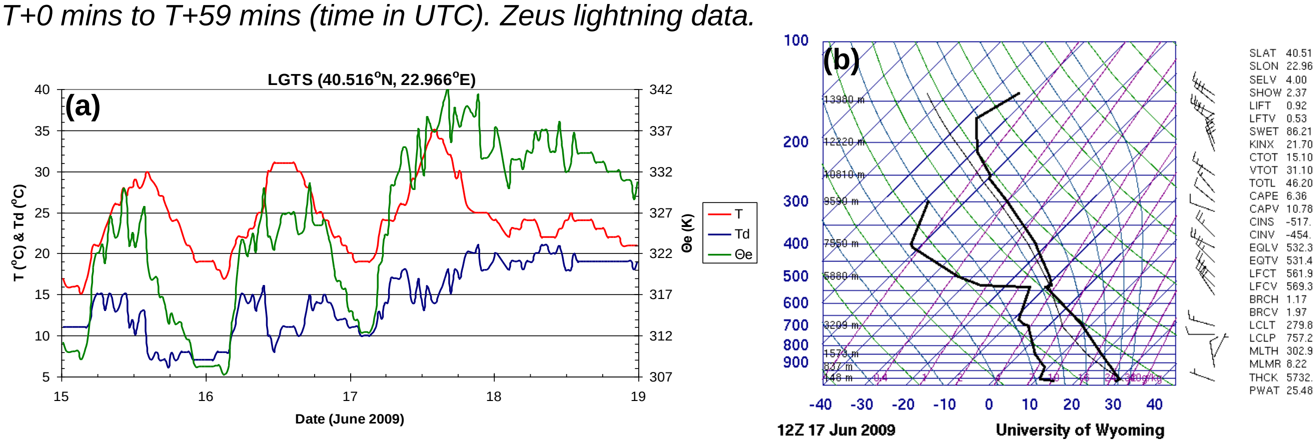
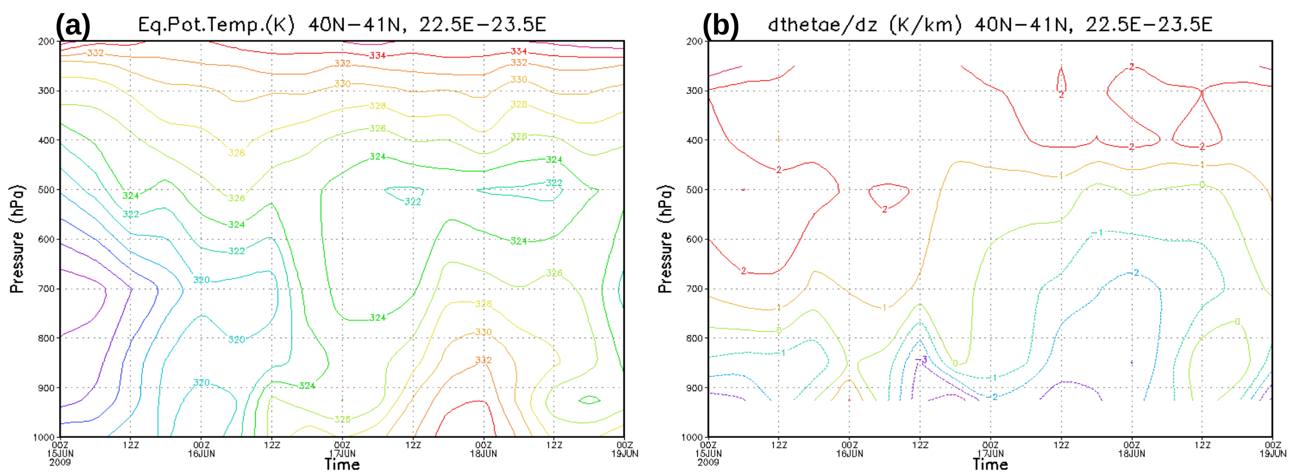


Figure 4: a) Timeseries of 2m temperature (°C), dew point tempetature (°C) and equivalent potential temperature (K) at Thessaloniki airport during 15-18/06/09 and b) sounding at Thessaloniki airport at 1200 UTC, 17/06/09.

The hovmoller diagram of the area-averaged θ_e (40°N-41°N, 22.5°E-23.5°E) and its vertical gradient (Figures 5a, b) suggest that potential instability was responsible for the convective activity of the event. During the previous two days (i.e. on 15 and 16 June) the vertical gradient of θ_e was negative in a shallow layer below 800 hPa. However, this potentially unstable layer (of negative $\partial\theta_e/\partial z$) became deeper on 17 June and it reached 500 hPa just before the triggering of the event. The θ_e difference between 500 hPa and 925 hPa in the area of interest maximized from 1800 UTC on 17/6/09 to 0000 UTC on 18/6/09 with values up to -12 K. The increase of the potential instability on 17 June was due to the synoptic scale flow that advected high θ_e air at low-levels (0.2-0.4 K/hr) and low θ_e air in the mid-troposphere (up to -0.4 K/hr; Figure 5c).

At low-levels a transient anticyclone moved from western to central Europe on 16 June and extended to Balkans in the early hours of 17 June. This pattern induced low-level divergence north of Greece that promoted the southward advection of warmer (during the first half of 17/06) and mainly moister air masses in the area of interest before the triggering of the first burst. At 0000 UTC on 18 June the anticyclone was centered over Balkans, the isobars exhibited an east-west orientation over northern Greece and the Aegean Sea, and their gradient increased with time. As a result moist air masses were advected at low-levels from the northern Aegean sea to the area of interest and the θ_e increased further. At 500 hPa, a ridge prevailed over the Mediterranean (from Spain to Greece) during 15-17 June with its centre mostly located over southern Italy. The northerly flow that was observed over southern Balkans advected cold, low- θ_e air masses southwards in the mid-troposphere of the area of interest. This differential advection appears to be responsible for the deepening of the potentially unstable layer.

Potential instability means that if such an air mass is lifted bodily until completely saturated, it will become unstable in the parcel sense regardless of its initial stratification. Therefore, a mechanism that will force the potentially unstable air column to be lifted until saturation is necessary to trigger convection. It is suggested that this lifting mechanism was provided by the convergence zones that appeared at low-levels in the area of interest between 1200 and 1800 UTC on 17 June (Figure 6a) when the first convective burst was triggered and reached values stronger than $-4x10^{-5}$ s^{-1} locally in Thessaloniki (Figure 6b). Kotroni et al. (1997) have shown that convergence zones promote summer storm activity in Greece.



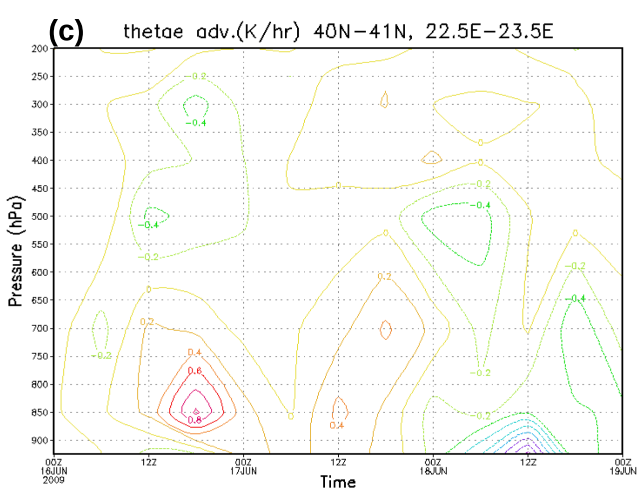


Figure 5. Hovmoller diagrams of area-averaged a) equivalent potential temperature (θ_e in K), b) vertical gradient of θ_e (K/km) and c) θ_e advection (K/hr) between 40°N-41°N, 22.5°E-23.5°E (this square appears in figure 2b). ECMWF analyses.

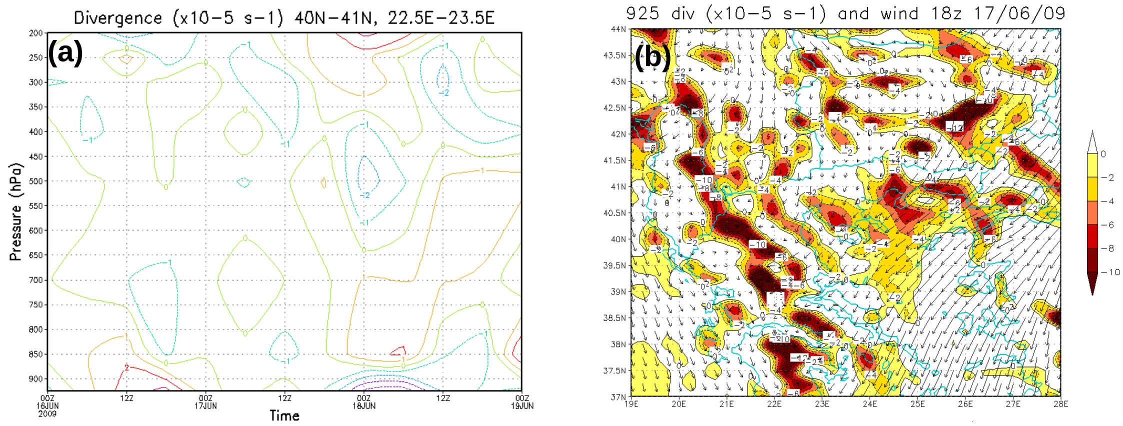


Figure 6. (a) Hovmoller diagram of area-averaged divergence (x10^{-5} s^{-1}) between 40°N-41°N, 22.5°E-23.5°E (this square appears in figure 2b) and (b) wind vectors and divergence (x10^{-5} s^{-1}) at 925 hPa at 1800 UTC, 17/06/09 (only negative values are shaded). ECMWF analyses.

4. Numerical Experiments

The aim of the numerical experiments is to investigate the performance of the WRF-ARW model to simulate the lightning activity of this event through LPI under different microphysical parameterizations. Eight experiments were conducted in analysis mode using identical setup (described in section 2), initial and boundary conditions, but, different combinations of microphysical parameterizations. The model was initialised at 1200 UTC on 17 June 2009 (approximately 6 hours before the first convective burst) and was integrated until 1200 UTC on 18 June.

The LPI (J/kg) is defined as $LPI = 1/V \iiint \varepsilon w^2 dxdydz$ where V is the volume of air in the layer between 0°C and -20°C (the charging zone), w is the vertical wind speed (m/s) and ε is a dimensionless number (between 0 and 1) that depends on the model mass-mixing ratios of snow, cloud ice, graupel and total liquid water (Yair et al. 2010). This index is nonzero only within the charging zone and is computed within the cloud volume. Figure 7 presents the maximum hourly value of LPI for each simulation together with the hourly number of lightning strikes from Zeus (same as figure 3d). The maximum hourly LPI corresponds to the spatiotemporally maximum value in the area of interest (40°N-41°N, 22.5°E-23.5°E) at each hour (derived from 5-min WRF output). It represents the maximum predicted potential for charge generation and separation that may lead to lightning activity in the area of interest. It seems that all simulations represented the potential for lightning activity and threat in general agreement with observations. The simulation with the recently developed Milbrandt-Yau scheme not only simulated two separate periods of activity, but also predicted their duration in good agreement with the Zeus data. On the other hand, the use of the Thompson V3.1 scheme resulted to only one episode. Regarding, the initial time of the activity it was predicted with a lag that ranged from 1 hour (Goddard, Milbrandt-Yau, WDM6) to 5 hours (Thompson V3.1). Moreover, the former schemes produced the best quantitative representation of the precipitation associated with the event at AUTH and LGTS stations (Figure 7). A summary of the performance of the simulations is produced with the use of contingency tables and the statistical scores of BIAS, Probability of Detection (POD), False alarm ratio (FAR) and Equitable Threat score (ETS) (Wilks 1995, Katsafados 2003). In these tables, lightning activity was considered when the hourly strikes were more than 0 and was predicted through WRF-LPI when the maximum hourly LPI was greater than 0 in the area of interest (40°N-41°N, 22.5°E-23.5°E). The scores of each experiment were derived by 24 pairs of Zeus vs WRF-LPI values. Figure 8 shows that most of the simulations exhibited very satisfactory scores and the ones with the schemes of Goddard, WDM6 and Milbrandt-Yau were systematically among the best. These three schemes resulted to the highest ETS scores with values ranging from 0.5 to 0.6. On the other hand, the Thompson V3.1 and V3.0 schemes exhibited the poorest scores in almost all statistics. This was a first analysis of the performance of WRF-ARW to predict the lightning activity and threat through LPI. Future analysis will not simply take into account the occurrence/prediction (or not) of lightning activity, but will also consider the strength of actual activity, the magnitude of LPI and their spatial distribution.

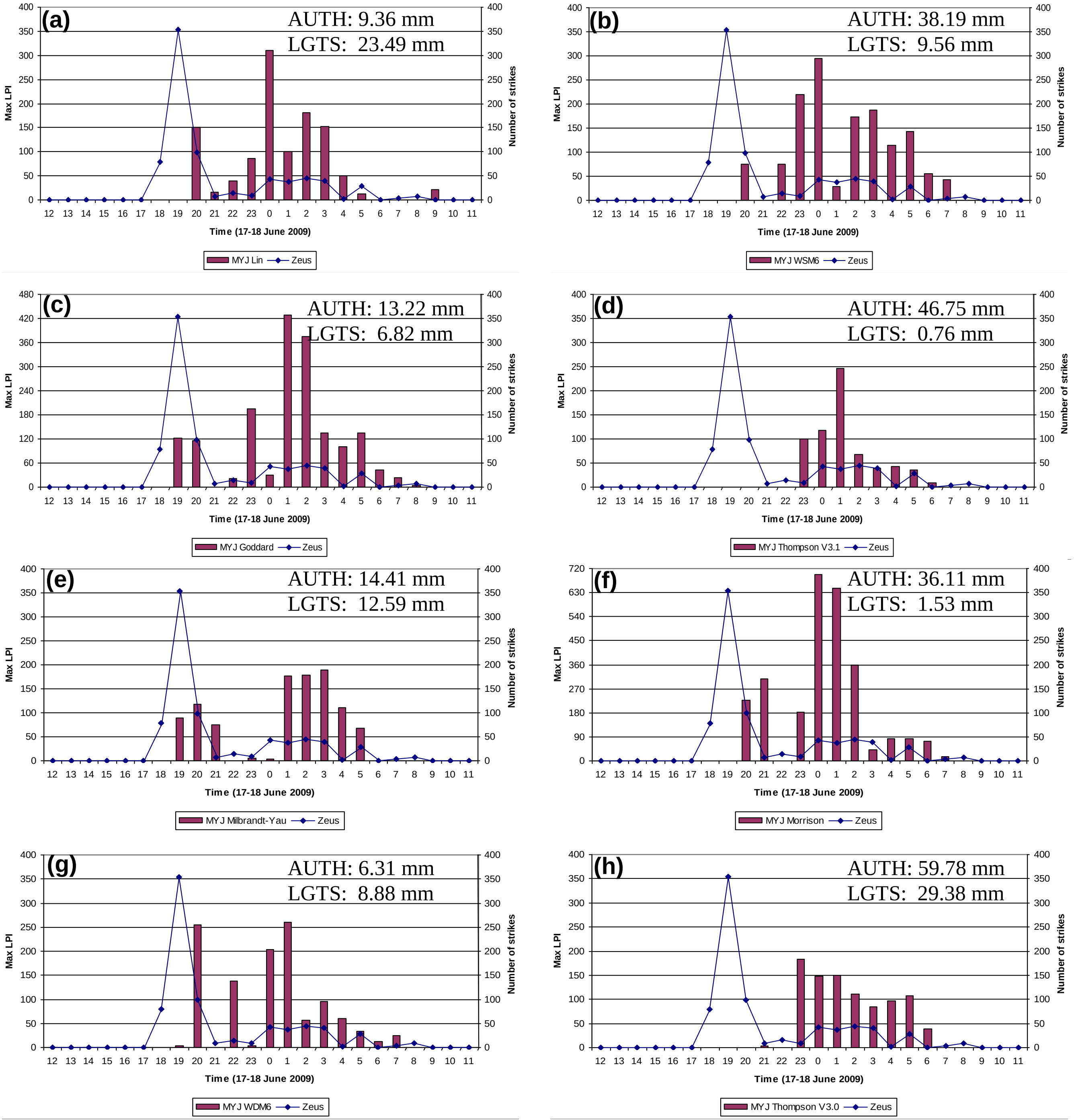


Figure 7. Timeseries of maximum hourly LPI (columns) and hourly accumulated number of lightning strikes (line) from Zeus (in the area between 40°N-41°N, 22.5°E-23.5°E), in the simulations with a) Lin, b) WSM6, c) Goddard, d) new Thompson V3.1, e) Milbrandt-Yau, f) Morrison, g) WDM6 and h) old Thompson V3.0 microphysical schemes. Time in UTC. The WRF precipitation between 18z, 17/06/09 and 06z, 18/06/09 at the locations of AUTH and LGTS appears on the top-right corner of each panel.

5. Conclusions

- During 17-18 June 2009 the city of Thessaloniki and several regions of central Makedonia were affected by impressive cloud-to-ground and intracloud lightnings associated with convective storms. The activity was characterized by two bursts and noticeable spatial variability of precipitation.

- Potential instability that resulted from differential θ_e advection at low-levels and in the mid-troposphere together with low-level convergence appeared to be responsible for the event.
- WRF-ARW simulations represented the potential for lightning activity and threat, through LPI, in general agreement with observations. The sensitivity experiments with Goddard, WDM6 and Milbrandt-Yau schemes exhibited the highest statistical scores, lowest precipitation errors and predicted the initial time of the event with a lag of only one hour. Future analysis will also consider the strength of actual activity, the magnitude of LPI and their spatial distribution.

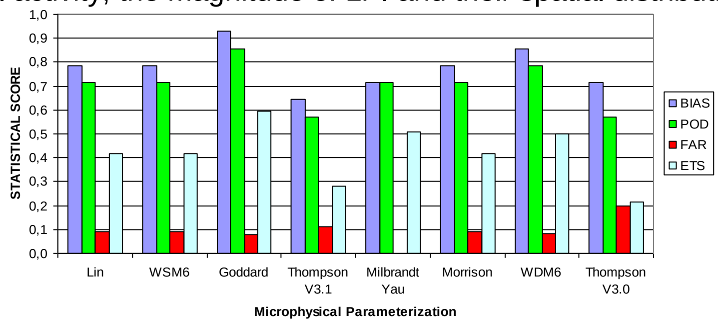


Figure 8. Bias, probability of detection (POD), false alarm ratio (FAR) and equitable threat score (ETS) of lightning activity versus microphysical parameterization. The scores correspond to the area between 40°N-41°N, 22.5°E-23.5°E and were derived by 24 pairs of Zeus measurements vs WRF-LPI. The lightning activity was represented by the maximum hourly predicted value of LPI and the hourly number of strikes (Zeus) both being greater than 0.

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