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SYNOPTIC AND MESOSCALE ANALYSIS OF HAILSTORMS OVER CROATIA ON 22 AND 23 JUNE 2007

Sinoptička i mezoskalna analiza tučonosnih oluja iznad Hrvatske 22. i 23. lipnja 2007.

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Abstract: A case of severe convective development affecting Croatia on 22 and 23 June 2007 is analyzed by means of synoptic material, satellite, radar and lightning data as well as hailpad data and hail observations. The development occurred during the passage of a cold front in strong upper-level south-westerly flow, bringing warm and humid air from the West Mediterranean. The onset of convection was triggered by the orographic lifting on the islands and later on the Dinaric Alps. A supercell developing in the North Adriatic split into two cells due to strong vertical wind shear and veering of the wind in the lowest 3 km. The right-moving cell with cyclonic rotation was longer living and the left one died out. Large hail was reported along the path of the cell. Later on, convective cells developing over the continental part of Croatia were of lower intensity, but still bringing hail of the hazelnut size. Hailpad measurements and hail observations show the distribution of hail in time and give the information about the sizes of hailstones. Aladin meso-scale model performance is tested for the development in the North Adriatic, showing that the model could successfully reproduce the environment and the conditions for severe convective development, however underestimating the precipitation amount.

***Keywords*:** Convective storms, supercell split, hail, model forecast

Sažetak: U radu je prikazana situacija 22. - 23. lipnja 2007. kad se niz konvektivnih oluja razvio iznad Hrvatske. U analizi je korišten dostupan sinoptički materijal kao i satelitski, radarski i podaci o električnom pražnjenju te podaci s tučomjera. Do razvoja konvektivnih oluja došlo je nakon prolaska hladne fronte, u jakoj jugozapadnoj visinskoj struji koja je donosila topao i vlažan zrak iz zapadnog Sredozemlja. Početak konvektivnog razvoja bio je potaknut dizanjem zraka na otocima, a zatim i na Dinaridima. Prikazan je tijek razvoja superćelije, nastale u sjevernom Jadranu, koja se razdvojila na dvije kovektivne stanice pod utjecajem jakog vertikalnog smicanja vjetra u prizemnom sloju i zakretanja njegova smjera u smjeru kazaljke na satu u prva tri kilometra. Konvektivna stanica koja se gibala udesno imala je ciklonalnu rotaciju i živjela je dulje dok je lijeva odumrla ubrzo nakon razdvajanja. Krupna tuča zabilježena je duž putanje konvektivne stanice. U kasnijem tijeku, do konvektivnog razvoja praćenog tučom došlo je iznad kontinentalnog dijela Hrvatske, no te su stanice bile manjeg intenziteta. Podaci s tučomjera pokazuju raspodjelu tuče u vremenu i daju informaciju o veličini zrna tuče. Operativni model Aladin primjenjen je za simulaciju razvoja u sjevernom Jadranu. Rezultati pokazuju da je model uspješno reproducirao uvjete za konvektivan razvoj, no podcijenio intenzitet i količinu oborine.

Ključne riječi: konvektivne oluje, razdvajanje superćelije, tuča, prognoza modela

1. INTRODUCTION

Severe convective events occur in Europe rather frequently in summer months. Due to the associated risk of damage caused by lightning, heavy rainfall or hail they are of a great interest to the broad public. In Croatia severe convective development occurs mainly in the south-westerly flow on the leading side of the upper-level troughs moving across Central Europe (Mikuš et al., 2012), as in the case described by Strelec Mahović and Drvar (2004). If the conditions are favourable convective clouds frequently grow into larger convective systems such as super-cells, multi-cell storms or squall lines, which always cause severe weather and sometimes serious damages (e.g. Strelec Mahović et al. 2007). A precise forecast of convection is therefore one of the most important tasks for the forecasters. Development and movement of convective clouds and systems can be followed in satellite and radar imagery as well as in lightning data but the problem of numerical forecast and early warning of the phenomena connected to convection is still an issue not completely resolved.

The study deals with a case of severe convective development over Croatia on the 22 and 23 June 2007. These events were only a small part of a series of severe thunderstorms developing over Central Europe from 20 to 23 June 2007. During these four days large areas of Germany, Austria, Czech Republic and Croatia were affected by heavy thunderstorms, causing damage in millions of Euros. The series of convective events started on the 20 June with the development of a squall line, which during the next hours moved slowly to the east and dissipated till the end of the day. From the evening of the 20 June to the noon of the 21 June several supercells crossed the southern parts of Germany. During the night a mesoscale convective complex (MCC) moved from south-western part of Germany to the north-northeast. Heavy precipitation, up to 70 mm/h, was observed as well as large hail in several places. On the 21 June Czech Republic was also a scene for a series of convective developments starting already in the morning hours with a mesoscale convective system (MCS) on the border between the Czech Re-

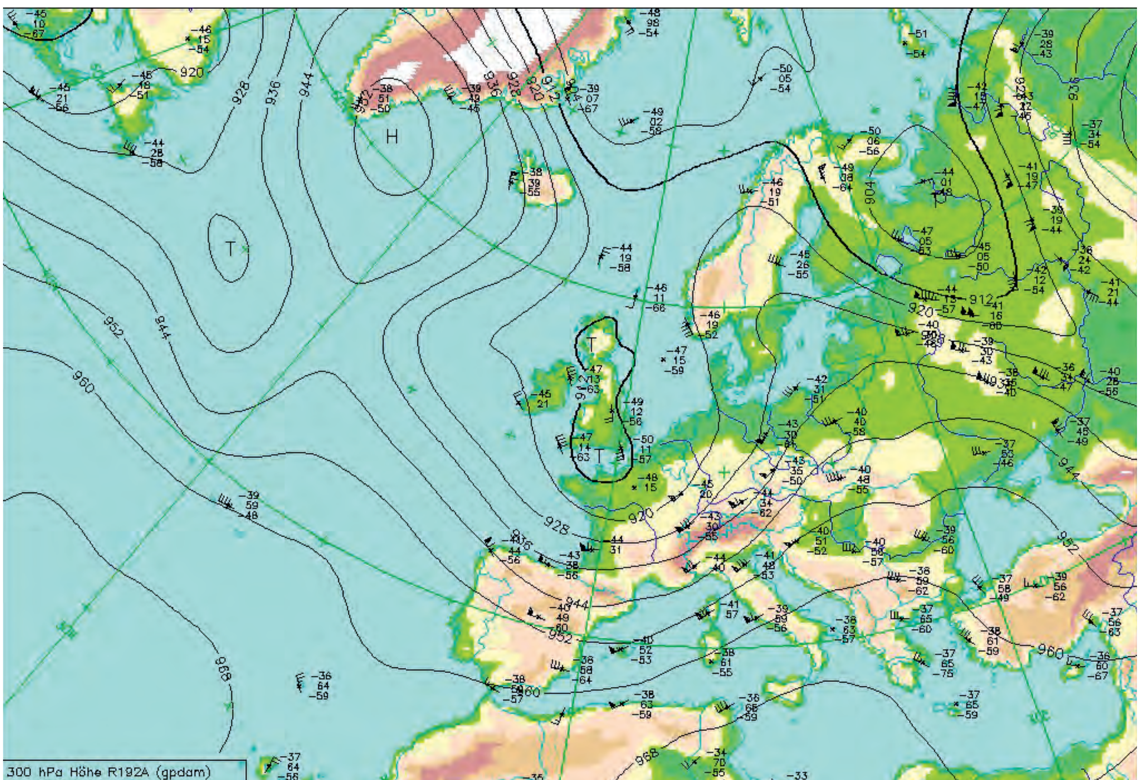

Figure 1: Height of 300 hPa level, analysis for 22 June 2007, 12 UTC (source: Deutsche Wetterdienst).

Slika 1: Visinska sinoptička karta, geopotencijalna visina plohe 300 hPa, analiza, 22. lipnja 2007. u 12UTC.

public and Poland. In the afternoon hours on 22 June, with increasing insolation, another MCS developed, moving over lower Austria and later in the evening of the same day development also started in Croatia.

For a thorough assessment of this convective case both synoptic-scale and mesoscale analyses are essential. Therefore the first part of the analysis will give an overview of synoptic conditions responsible for the instability that favoured convective development. This will be provided using analyses by the Deutscher Wetterdienst (DWD) and the European Centre for Medium-Range Weather Forecasts (ECMWF) model data. Remote sensing data including satellite, radar and lightning will give the opportunity to monitor the relevant development. Finally, the ALADIN/HR model results, giving the mesoscale perspective, will show how well a numerical model can capture the details of these events.

2. SYNOPTIC SITUATION

The large-scale situation preceding the storms was characterized by a deep upper-level trough connected to the low above the British Isles, whereas the Central and East Europe was under the influence of a pronounced ridge, as seen in the 300 hPa height field on 22 June 2007 at 12 UTC (Fig. 1). Due to large pressure gradients in the upper levels, southwesterly and westerly winds were strong over West Europe. At the surface level the region of central and north-western part of Europe was influenced by a shallow low with one centre over the southern part of Scandinavian peninsula and the other south of the Alps, over North Italy and North Adriatic. Connected to the latter, a cold front was passing across the western part of Croatia in the night of the 23 June, as seen in Fig. 2.

There are three ingredients necessary for the development of deep convection: sufficiently deep moist layer in the low or mid-troposphere, a steep lapse rate and sufficient lifting to allow the parcel to reach its level of free convection (Doswell, 1987, Johns and Doswell, 1992). The first condition, moisture, was in this case being advected from the Mediterranean, together with warm air, in a

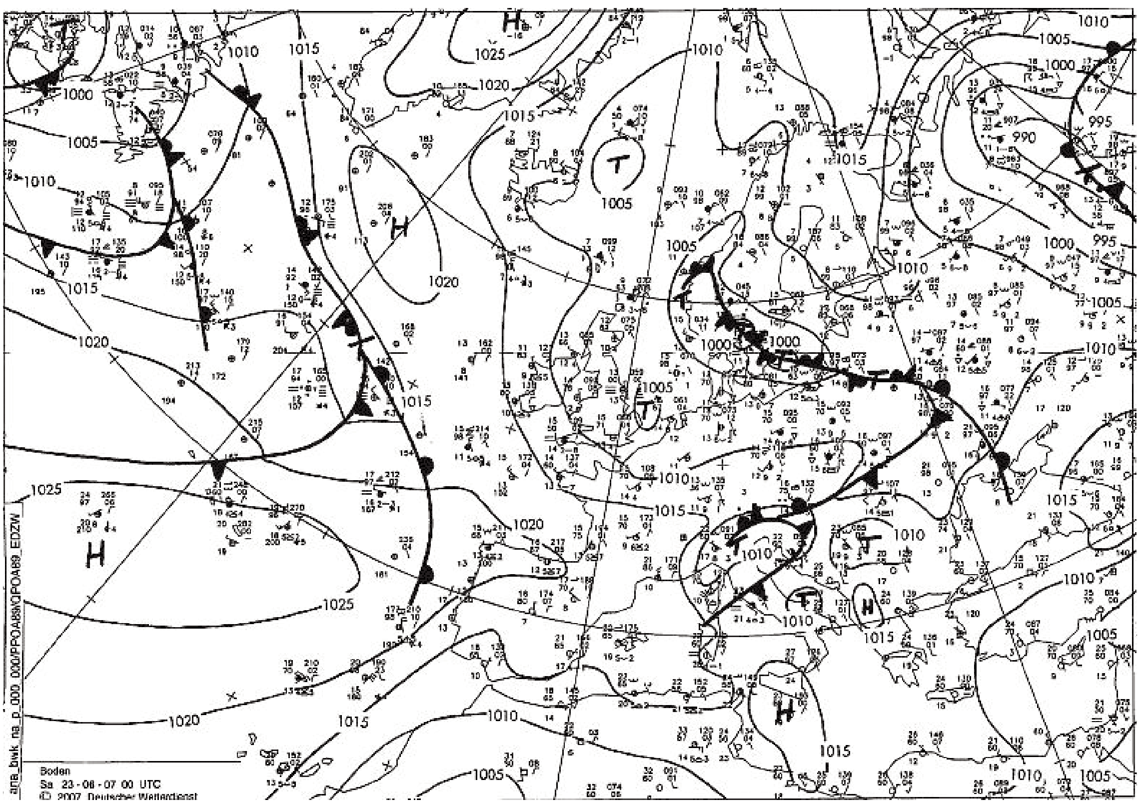

Figure 2: Mean sea-level pressure analysis with fronts, 23 June 2007, 00 UTC (source: Deutsche Wetterdienst)

Slika 2: Prizemna sinoptička karta, tlak zraka na razini mora s frontama, 23. lipnja 2007. u 00UTC.

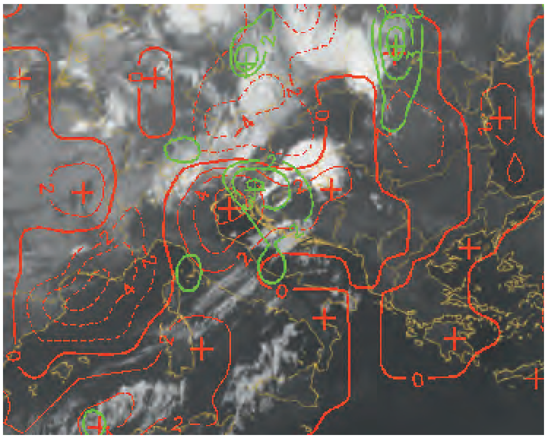

Figure 3: Temperature advection at 700 hPa (warm advection–solid red line, cold advection - dashed red line) and positive vorticity advection at 500 hPa (green line) (ECMWF), overlaid on Meteosat 9 IR 10.8 μm satellite image for 23 June 2007, 00 UTC.

Slika 3: Infracrvena slika valne duljine 10.8 mikrometara sa satelita METEOSAT 9 za 23. lipnja 2007. u 00UTC s podacima analize modela ECMWF, temperaturna advekcija na 700 hPa (topla advekcija – puna crvena linija, hladna advekcija – crtkana crvena linija) i advekcija pozitivne vrtložnosti na 500 hPa (zelena linija).

south-westerly stream. At midnight of the 23 June over the whole region of Italy and Croatia, especially over the North Adriatic, warm advection was present in the mid-troposphere, as indicated in Fig. 3. Additional synoptic forcing was provided by the jet stream-related vorticity advection maximum on the cyclonic side of the upper-level trough, also seen in Fig. 3. At 18 UTC the jet-streak was entering North Adriatic and strong ascent in this area was reinforced by the upward motion in the left exit region of the jet streak (Ucellini and Johnson, 1979).

The fact that the atmosphere was very unstable, was confirmed by the stability indices, particularly Showalter index with values below -3 in the region southeast of the Alps. Moreover, equivalent potential temperature at 850 hPa was between 323 and 328 K. This, however, only shows that the synoptic circumstances were favourable for convective development (Bluestein, 1993), but the magnitude of the large-scale ascent is always too small to provide the needed lift in reasonable time. In other words, for the process of such intensity there must have been a mesoscale process in addition. In this case a reasonable assumption is that orographic lifting has triggered the ascent strong enough to cause the development of severe convective storms. Since during the whole period in regard the governing flow over the Central Europe was south-westerly, the specific orography of the shore of North Adriatic, with steep coastal mountain ridges, played a major role both in generating prefrontal and in intensifying frontal precipitation. In an unstable environment, such as this one, the lifting of moist air over the barrier was accompanied by deep convective development in particular places along the coast.

3. LOCAL CONDITIONS

In the late evening of the 22 and during the night of the 23 June 2007, the region of the North Adriatic and the adjacent mountainous area, and later on the north-eastern and eastern part of Croatia, were devastated by a series of hailstorms. Hail on the island Rab in the North Adriatic was the size of eggs or even peaches (greater than 36 mm in diameter); at the other parts hail was the size of hazelnuts or walnuts (9-20 mm). Numerous large property damages were reported. It seems that convection over the island Rab was triggered by the orography of one of the islands southwest of it, probably the hill Televrina on the Lošinj island, during the passage of a cold front.

3.1 Supercell in the North Adriatic

To assess the conditions in which the onset of convection occurred, vertical profile of the atmosphere is analyzed by means of the data from Zadar sounding station, which was the nearest to the location of strong convection over the island Rab. In skew T-log p diagram in Fig. 4 the profiles of temperature and dewpoint temperature indicate very unstable atmosphere. Convective available potential energy (CAPE), a measure of the amount of energy available for convection, has a value of 2884 J/kg which can be considered as an indication for high possibility of convective development. This type of sounding, characterized by extreme instability, but containing a cap, a region of temperature inversion below the level of free convection, is often called the “loaded gun” or a Type_B sounding (Johns and Doswell III, 1992).

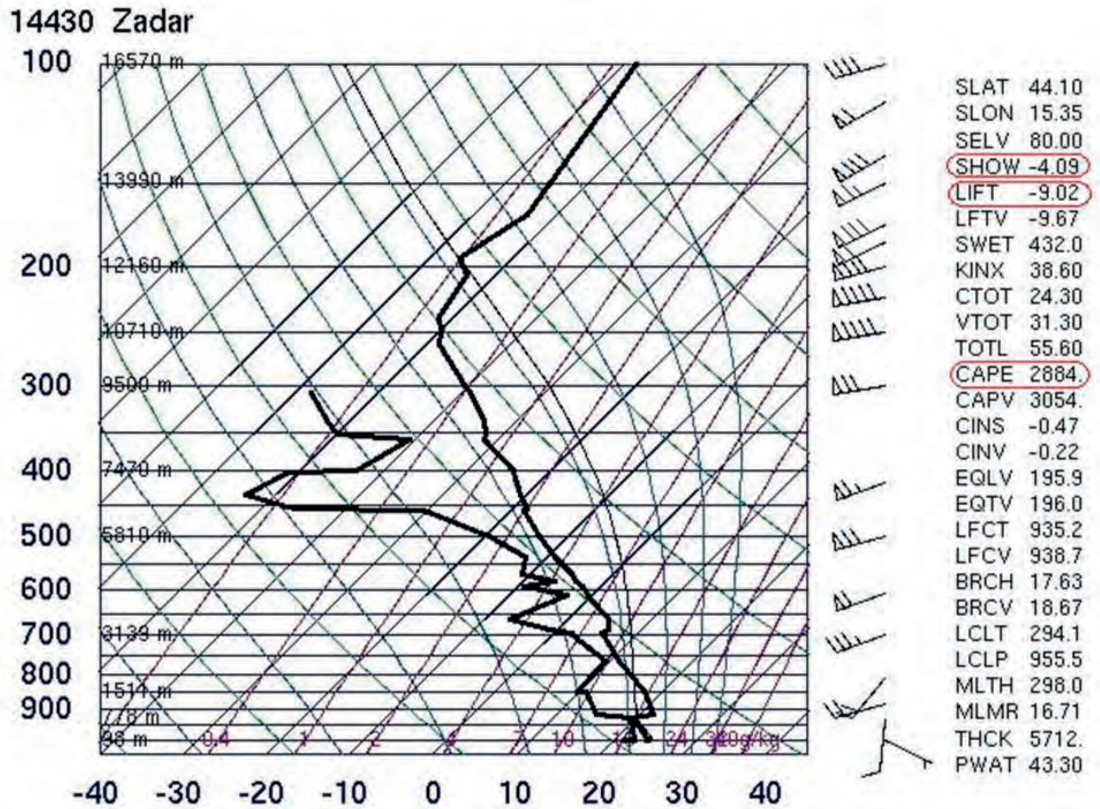

Figure 4: Skew T - log p diagram of Zadar sounding on 23 June 2007, 00 UTC. The values of the stability indices are listed to the right of the image.

Slika 4: Skew T – log p dijagram radiosondaže za Zadar za 23. lipnja 2007. u 00UTC. Indeksi nestabilnosti dani su desno od dijagrama.

Although the presence of the temperature inversion in the lowest layers could have inhibited the development, the presence of triggering mechanisms, such as frontal passage and orographic lifting, was obviously strong enough for severe convection to occur.
Besides CAPE, stability indices listed to the right of the diagram in Fig. 4, also show quite a big risk for severe convection. Very strong wind, especially above 3 km where the wind speed was above 30 m/s, shows south-westerly direction. In the lower troposphere, between 850 and 500 hPa, large vertical wind shear is present (wind speed rising from 10 to 35 m/s), as well as the veering of the wind in the first 800 m above the ground. All these characteristics point to the fact that the state of the atmosphere in the night of the 23 June was favourable for convective development.

The first radar echo indicating strong convection appeared at 1915 UTC. The data are obtained by the radar in Bilogora, which is one of two Croatian radars located in the northern part of the country. It is an S-band, Doppler radar with the beam wavelength of 10 cm and maximum range of 240 km. Since there are no radars along the Adriatic coast these were the only data available for the analysis of the development in the North Adriatic. The intensity of convection is depicted by maximum reflectivity in dB*Z*, where hail is likely at 50 dB*Z*. In Fig. 5a, at 1930 UTC, within the cell in the lower left corner, radar reflectivity is over 60 dB*Z*, meaning that hail occurrence is highly probable. Indeed, the egg-sized hail was witnessed in the respective area, on the island Rab. Closer inspection of the cell shows that it consists of two cells which are here still tight to each other. 15 minutes later, at 1945 UTC (Fig. 5b) convective cell moved towards the inland, but the appearance in the radar image suggests that the original cell has split into two cells, both having reflectivity above 55 dB*Z*.

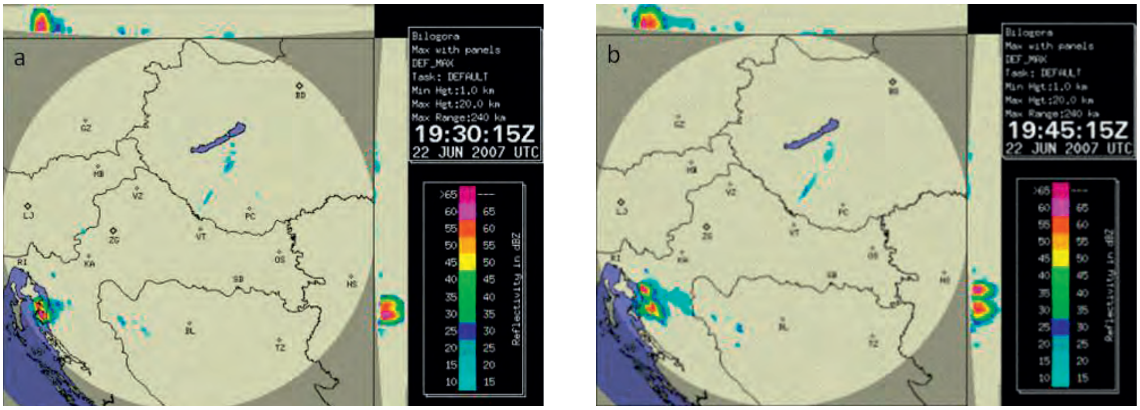

Figure 5: Radar maximum reflectivity in dB*Z* on 22 June 2007, 1930 UTC (a) and 1945 UTC (b). A cell developing in the North Adriatic is seen in the lower left corner. A cell split is seen in the lower left corner and in the vertical view to the right of the image (b).

Slika 5: Maksimum radarske refleksivnosti u dBZ 22. lipnja 2007. u 19:30UTC (a) i 19:45UTC (b). Ćelija koja se razvija u sjevernom Jadranu vidljiva je u donjem lijevom kutu. Podjela ćelije na dvije vidljiva je u donjem lijevom kutu i u vertikalnom prikazu s desne strane slike (b).

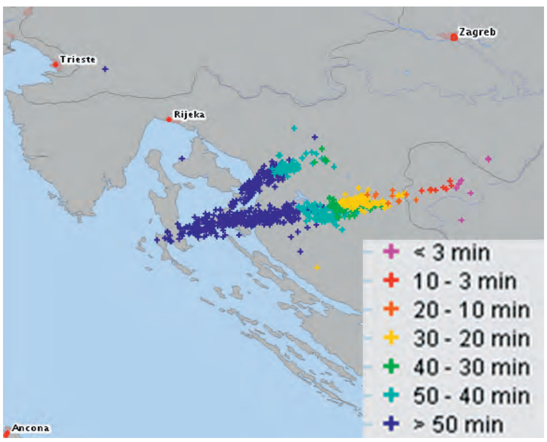

Figure 6: Lightning data from LINET lightning network. Lightning strokes between 1800 UTC and 2045 UTC are shown. Cell split and the paths of the cells are clearly indicated.

Slika 6: Podaci električnog pražnjenja iz LINET mreže. Prikazane su munje između 18:00UTC i 20:45UTC. Jasno se vidi podjela ćelije i putanje dvije nove ćelije.

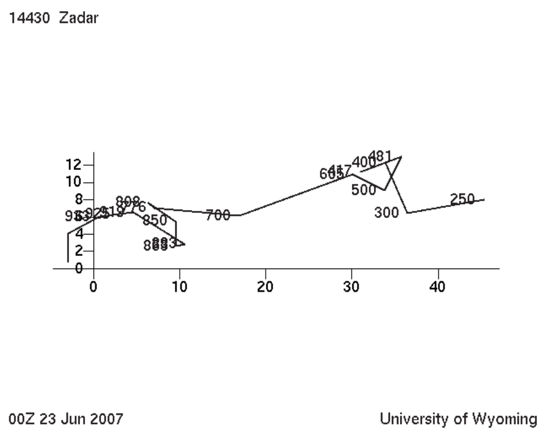

Figure 7: Wind hodograph from Zadar sounding station at 00 UTC on 23 June 2007. Clockwise curvature of the hodograph below 800 hPa is seen.

Slika 7: Hodograf za radiosondažnu postaju Zadar u 00UTC 23. lipnja 2007. Primjećuje se zakrenutost linije hodografa u smjeru kazaljke na satu ispod 800 hPa.

During the next few time steps the left cell has weakened and the right one was still showing a strong signal. Splitting of the original cell into two, their movement relative to the mean wind and the dissipation of the left cell can also be nicely recognized in lightning data, coming from the LINET network (Betz et al.,2009), shown in Fig. 6.

The process of splitting requires strong environmental vertical wind shear, larger than 20 m/s in the layer below 4 km. In this case, according to Zadar sounding, the shear below 4 km was larger than 25 m/s. Moreover, clockwise or counter-clockwise hodograph curvature must exist in the lowest few kilometres above ground level. Wind hodograph from Zadar sounding (Fig. 7) shows a clockwise turning in the lower atmosphere (the lowest 3 km).

In the environment of a strong vertical wind shear the strong tilting of convective cells tends to delay the initial storm development even in a thermodynamically favourable environment. The development under such conditions may be followed by a split into two storms, moving to the left and right of the mean wind (Holton, 1992). In general, the left-moving storm has the anticyclonic rotation whereas the cyclonic supercell is often observed to propagate to the right of the mean wind in the Northern Hemisphere. Usually the left-moving storm dies rapidly while the right-moving storm slowly evolves into a rotating cell with a single updraft core. According to Grasso (2000), observations show that the left-moving updraft tends to dissipate approximately 15 min after the splitting process. The right-moving cell, however, may exist for up to a few hours. The left cell in this case decayed after 20 minutes, while the right one lived for approximately an hour. Idealized modeling studies suggest that this behavior is related to the clockwise turning of the environmental shear vectors with height. The interaction between the environmental shear and the updraft of the storm produces a high–low pressure couplet oriented downshear. This pressure pattern results in vertical accelerations favourable for the right mover, whereas the same process inhibits upward motion for the left mover. According to Holton (1992), such supercells often produce heavy rain and hail, which was the case also here.

Although the radar and lightning data clearly indicate the split of the cell, in the satellite data the cell appearance suggests that there is only one big thunderstorm (Fig. 8). The reason for that is probably the common cirrus anvil of the two storms, which covers the structure underneath. However, also the characteristics of the storm top in the satellite images suggest that severe convection is taking place. In Fig. 8 temperature-enhanced Meteosat 9 infra-red 10.8 μm image shows the storm over the central part of Croatia. Temperature enhancement of the infra-red image resolves the structure of the cloud tops in more detail. This enables the recognition of the cloud features like cold-U/V shape and cold-ring shape, which can be the indicators of the storm severity (Setvak et al., 2008, Iršić Žibert and Žibert, 2012). In this case, a ring shape of the coldest part of the cloud top is seen. Lower (southward) part of the ring is more prominent (colder) and within that part two spots with temperature lower than -60 °C can be seen. These indicate the locations of the overshooting convective cloud tops. Recent investigations done by Bedka (2010) and Mikuš and Strelec Mahović (2013) showed that the appearance of the overshooting tops is often connected to severe weather on the ground.

More detailed analysis of the stages of convective development would be possible with the data from solar channels, for example 3.9 or 1.6 μm reflectivity, which would enable the distinction between ice and water cloud particles as well as the assessment of the cloud-top particle size (Setvak et al., 2003). This, in combination with 0.6 μm reflectivity, would enable

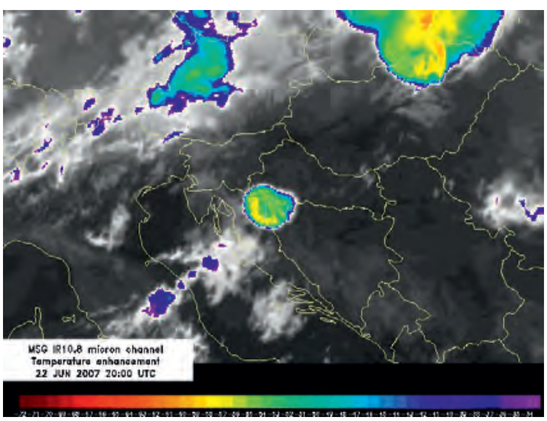

Figure 8: Color-enhanced Meteosat 9 IR 10.8 μm image for 22 June 2007, 2000 UTC.

Slika 8: Obojani prikaz infracrvene slike valne duljine 10.8 mikrometara sa satelita METEOSAT 9 za 22. lipnja 2007. u 20:00UTC.

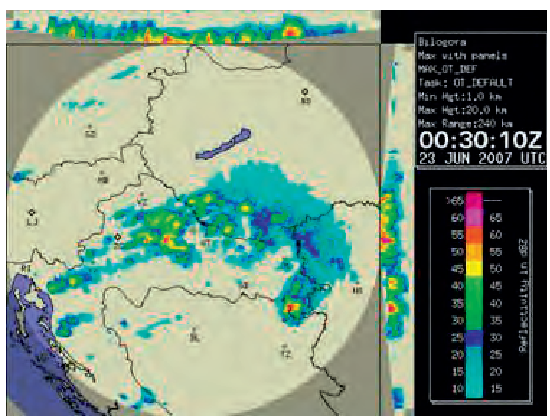

Figure 9: Radar maximum reflectivity in dBZ on 23 June 2007, 0030 UTC.

Slika 9: Maksimum radarske refleksivnosti u dBZ 23. lipnja 2007. u 00:30UTC.

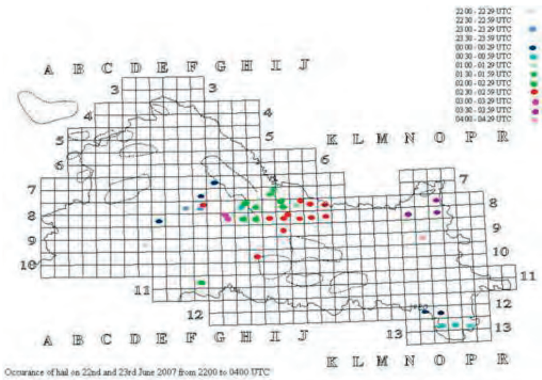

Figure 10: Distribution of hail in the continental part of Croatia during the night from 22 to 23 June 2007, based on the hail-pad measurements and hail observations. Different colours indicate different times of hail occurrence.

Slika 10: Raspodjela tuče u kontinentalnoj Hrvatskoj tijekom noći s 22. na 23. lipnja 2007.

the identification of the most active part of the convective cloud (Strelec Mahović and Zeiner, 2009; Kerkmann, 2005). However, since the development was taking place mainly during the night, it was only possible to use the infra-red channel data.

3.2 Hailstorms over the inland

Settled in the mid latitudes of the Northern Hemisphere, the continental part of Croatia is exposed to frequent occurrence of severe thunderstorms and hail, mainly in the summer months. In the 1960s, aiming to protect agricultural production and reduce damage from hail, a hail suppression system was introduced to the area located between the river Sava, to the south, Drava to the north and Mura to the north-west (Počakal et al., 2009). Over the continental part of Croatia hail observations and measurements are done during spring and summer months by the observers on the hail stations using the hail-pad network. For better

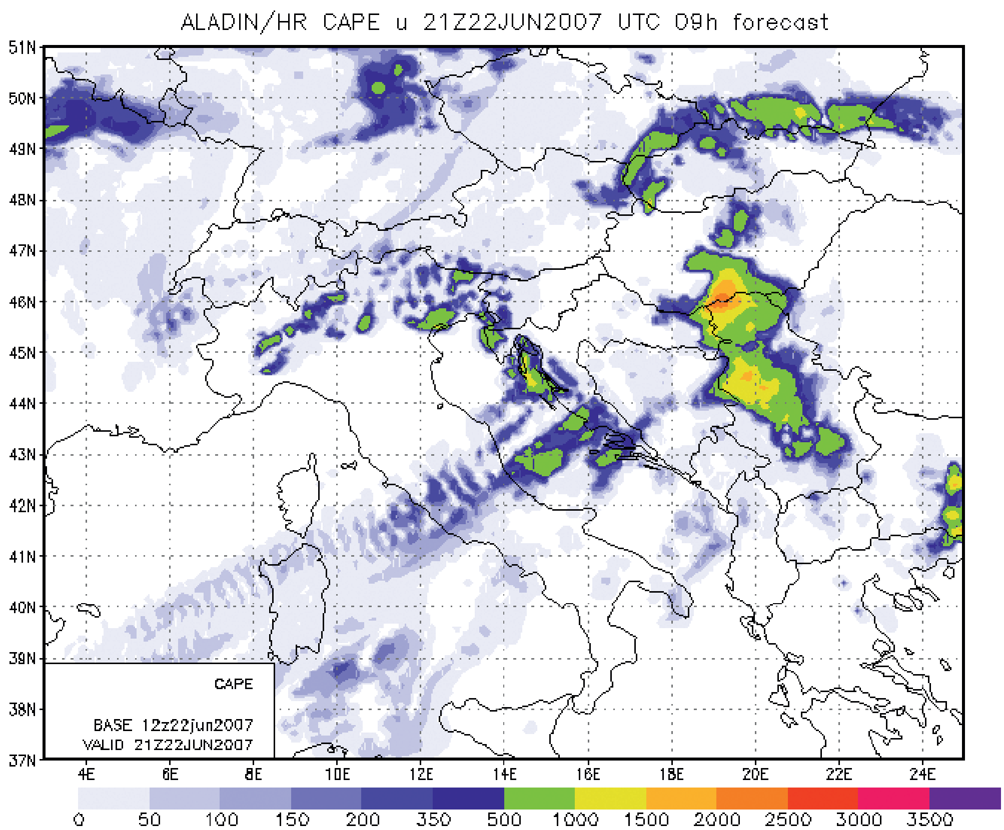

Figure 11: CAPE forecast by ALADIN/HR model valid for 22 June 2007, 2100 UTC.

Slika 11: CAPE, prognoza modela ALADIN za 22. lipnja 2007. u 21:00UTC.

data analysis, the area is divided into 136 quadrants of 9×9 km in size (Počakal, 2003). In addition, the region is covered by 2 radars.

Convective system, analyzed in chapter 3.1, moved to the north-east, developing further, and the area of convective activity became larger.

The significant development occurred over the northern and north-eastern part of Croatia. Many single cells, some with radar reflectivity over 60 dB*Z* can be noticed in radar data in Fig. 9 and a lot of hail over the northern part of Croatia was reported. Hail occurred in the western, central and north-eastern part of Croatia (Fig. 10). The observed average hailstone diameter over the continental part was up to 25 mm with duration of hail from 2 to 10 minutes. According to the hail-pad measurements the maximum hailstone diameter was 24.9 mm and mean diameter was in many places exceeding 10 mm.

4. MODEL PERFORMANCE

Mesoscale analysis of the case was based on the ALADIN (Aire Limitee Adaptation Dynamique development InterNational) forecast model. Since the capability of the ALADIN model to predict heavy precipitation events over the eastern side of the Alps was verified during MAP (Mesoscale Alpine Program) by comparing the HRID (High Resolution Isentropic Diagnosis) vertical time cross-sections based on radio-sounding measurements and the ALADIN/LACE prognostic Temps (Ivančan-Picek et al., 2003), the present study is concerned mainly with the analysis of meteorological fields rather than the evaluation of model performance.

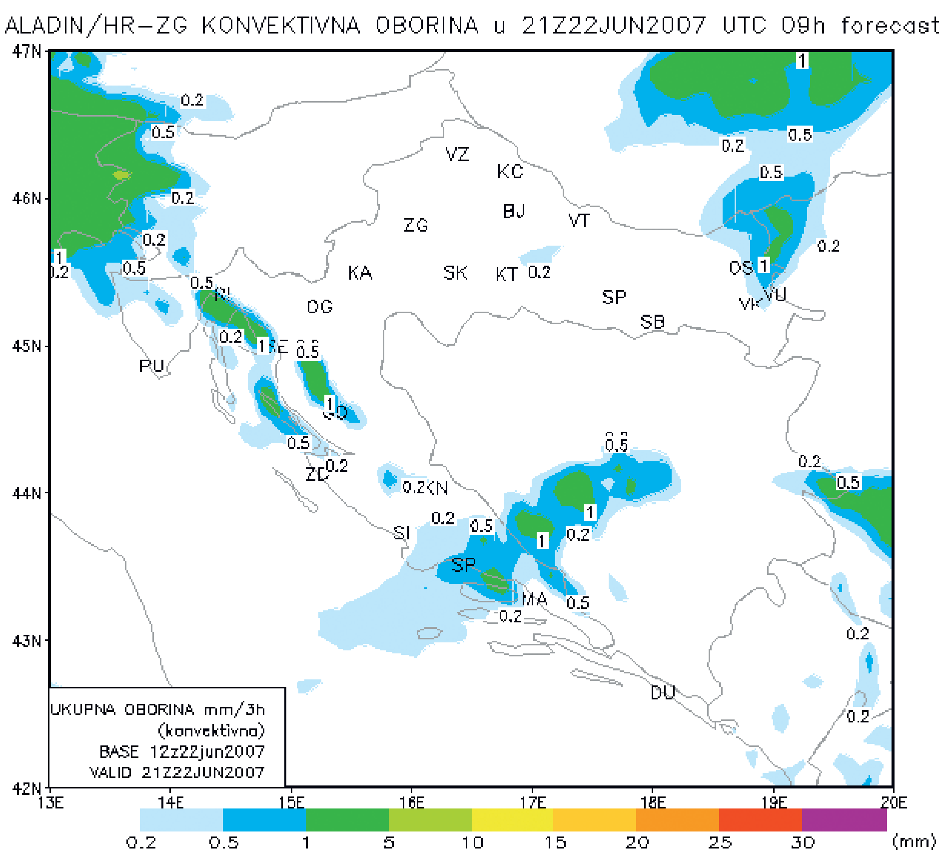

Figure 12: 3-hourly accumulated convective precipitation forecast by ALADIN/HR model valid for 22 June 2007, 2100 UTC.

Slika 12: Trosatna akumulirana konvektivna oborina, prognoza modela ALADIN za 22. lipnja 2007. u 21:00UTC.

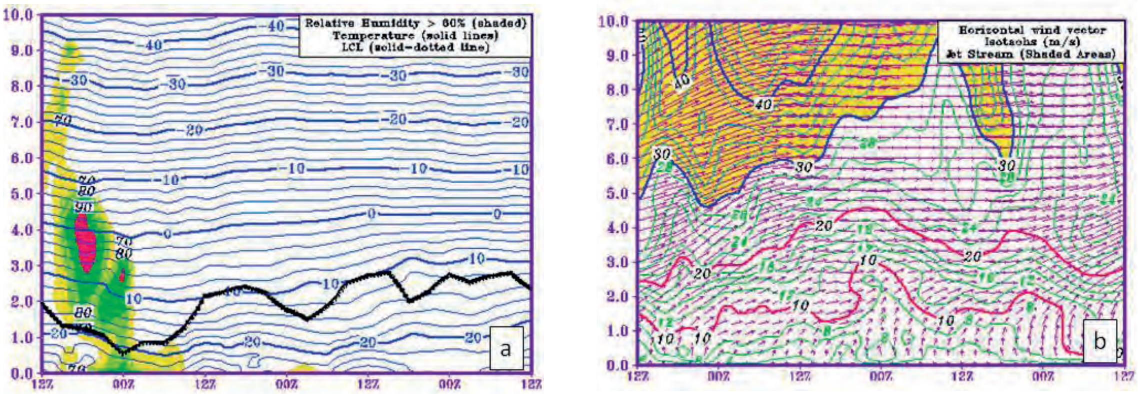

Figure 13: ALADIN/HR time cross-sections for the grid-point nearest to Rab island for 22 June 2007, 1200 UTC +72 hours. (a) Temperature isolines (blue), relative humidity greater than 60% (shaded) and Lifting Condensation Level (black solid line). (b) Horizontal wind vectors and isotachs. Jet stream is shaded.

Slika 13: Vremenski vertikalni presjeci za točku modela ALADIN/HR najbližu otoku Rabu za 22. lipnja 2007. od 12UTC za 72 sata unaprijed. (a) Izolinije temperature (plavo), relativna vlaga veća od 60% (sjenčano) i LCL (crne pune linije). (b) Horizontalni vektori vjetra i izotahe. Mlazna struja je žuto osjenčana.

Mesoscale non-hydrostatic ALADIN/HR model runs at the Meteorological and Hydrological Service of Croatia, two times a day (00 and 12 UTC), with spatial resolution of 8 km and the prognostic time interval of 72 hours. For the purpose of this case-study all model runs starting from 21 June 2007, 00 UTC were examined, analysing the parameters such as CAPE and other stability indices, precipitation, wind etc. The analysis showed that none of the model runs from 21 June 00 UTC till 22 June 00 UTC captured the processes satisfactory. Convection was predicted to develop too far to the south and with much lower intensity. The best performance was found for the 22 June 12 UTC run, in which stability parameters pointed to the correct location of the strongest convective activity. In Fig. 11 CAPE on 22 June 2007 at 21 UTC shows a maximum in the region of North Adriatic where, according to radar and lightning data in Figures 5 and 6 the development occurred.

K-index (not shown) indicated two broad unstable areas, one in the North Adriatic and the other stretching from central to north-eastern Croatia. Both areas were later hit by severe thunderstorms. As expected also by K index, showing the higher values at the Adriatic, the development in the North Adriatic was more severe. Convective precipitation from the model shows rather good accordance with real precipitation, but only regarding the position, not the amount. Namely, the stations in the North Adriatic experienced 10 to 20 mm of precipitation in a short while, while the model predicted less than 5 mm (Fig. 12).

Vertical structure of the atmosphere predicted by the model is depicted by the time cross-section in Figs. 13a and 13b. These are the cross-sections for the model grid-point closest to the island Rab. In Fig. 13a temperature isolines are combined with shaded area for relative humidity above 60%. Thick solid line stands for lifting condensation level. The model predicted convective development from 18 to 00 UTC, very close to the time of the hailstorm on the island Rab. Besides high relative humidity and lowering the lifting condensation level to 500 m in Fig. 13a, the structure of the forecast wind field in Fig. 13b is very similar to the profile from the sounding station.

In the lowest levels the wind was forecast to be south-easterly, veering with height and having south-westerly direction from about 1 km height on. Low level jet reaches down to almost 4 km at 00 UTC, which is comparable with radiosonde data in which the wind speed was greater than 17 ms^{-1} above 700 hPa level.

5. CONCLUSIONS

The analysis of severe convective development in Croatia in the night from 22 to 23 June 2007 showed that the atmospheric conditions above the region of Central Europe and Adriatic were favourable for convective development. Strong south-westerly upper-level stream was bringing warm and humid air from the Mediterranean and in the unstable air the islands in the North Adriatic as well as the Dinaric Alps served as triggers for convection. The most severe development occurred in the North Adriatic, bringing egg-size hail to the island Rab. Although rather small in size, the cell had all characteristics of a supercell, splitting into two cells with right-moving, cyclonic cell being longer living than the left-moving, anticyclonic one. Convection over the continental part later during the night was of lower intensity, but numerous thunderstorms were still bringing hazelnut sized hail to the northern parts of the country. Hail distribution is documented by hail-pad measurements and hail observations.

ALADIN/HR model performed satisfactory predicting the conditions for the development in the North Adriatic. Wind forecast captured the vertical structure with large vertical wind shear and veering of the wind in the lowest layers as well as the low-protruding jet. Stability parameters successfully reproduced the large instability in the North Adriatic and the time of development forecast by the 12 UTC model run on 22 June was very close to the time of the actual development. This shows that the meso-scale model ALADIN/HR could successfully reproduce the general conditions required for convective development, but not the intensity and the life-cycle of an individual convective system.

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