Doktorska disertacija – Sažetak
D.Sc. Thesis – Extended abstract

NUMERIČKE SIMULACIJE TUČE I INDEKSA POTENCIJALNOG RAZVOJA MUNJA NAD HRVATSKOM

Numerical simulation of hailstorms and lightning potential index over Croatia

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Sažetak:

Tuča i munje, jedan su od produkata olujnog vremena koji su povezani sa značajnim ekonomskim gubitcima u prometu, energetici, poljoprivredi, građevini i još nekim drugim granama gospodarstva. Iako relativno česte pojave na našem području, još uvijek predstavljaju izuzetno izazovan fenomen za simulaciju meteorološkim modelima i prognozu. Ovo proizlazi iz činjenice da procesi odgovorni za formaciju tuče i munja unutar olujnog oblaka još uvijek nisu u potpunosti poznati. Kako je tuča izuzetno lokalna pojava, jedan od najvećih izazova prilikom analize karakteristika tuče jest nedostatak izravnih mjerenja tuče na tlu.

Tijekom godina razvijeni su dijagnostički alati za simulaciju opažene tuče i munja – HAILCAST i indeks potencijalnog razvoja munja (engl. Lightning potential index, LPI). U ovom radu korištene su HAILCAST i LPI dijagnostike združene s modelom WRF (engl. Weather and Research Forecast) fine razlučivosti. Svrha je istraživanje sposobnosti modela WRF da reproducira atmosferske uvjete prisutne prilikom pojave tuče i munja u Hrvatskoj, ali i široj Alpsko-jadranskoj regiji te sposobnosti dijagnostičkih alata da reproduciraju opažene karakteristike tuče i munja. Provedena je detaljna analiza osjetljivosti rezultata modela WRF na odabir shema parametrizacije mikrofizike i atmosferskog graničnog sloja. Ispitana je robusnost rezultata modela WRF usporedbom s rezultatima mezoskalnog modela COSMO (engl. *Consortium for Small Scale Modelling*) (korištenog u nekoliko zemalja srednje Europe) prilikom simulacije slučaja tuče iznad Alpsko-jadranske domene. Konačno, koristeći model WRF ispitani su uvjeti prilikom nastanka (rano)jutarnje tuče na području Istre.

Rezultati pokazuju da današnji mezoskalni modeli mogu vjerodostojno reproducirati atmosferske uvjete prisutne prilikom pojave tuče u Hrvatskoj, ali i u široj Alpsko-jadranskoj regiji. Štoviše, dijagnostički alati za simulaciju tuče i munja pokazuju obećavajuće rezultate u simulaciji opaženih karakteristika tuče i munja iznad Hrvatske, ali i šire Alpsko-jadranske regije. Odabrani dijagnostički alati uspješni su u simulaciji prostornih značajki i intenziteta opažene aktivnosti munja. Slično, utvrđena je dobra uspješnost u simulaciji prostornih obilježja tuče izmjerenih radarskim produktima iz Švicarske te mreže tučomjera iz Hrvatske. Varijabilnost rezultata u odabiru mezoskalnog modela i postavkama pojedinog modela ukazuje na korist korištenja multimodelskog i/ili multifizičkog ansambla pri simulaciji i prognozi ovih događaja. Za kraj, utvrđeno je da se ranojutarnja tuča iznad Istre većinom javlja u ciklonalnim vremenskim tipovima. Osim sinoptičkih uvjeta, za nastanak konvekcije i tuče, bitnu ulogu predstavljaju i mezoskalni, ali i lokalni uvjeti. Trenutni modeli pokazuju dobru uspješnost u simulaciji odabranih događaja.

Dobiveni rezultati su obećavajući te ukazuju da bi analizirani dijagnostički alati mogli biti vrijedan doprinos operativnoj numeričkoj prognozi tuče, ali i klimatskoj ocjeni pojave tuče i munja u sadašnjoj i budućoj klimi. Ovo izravno doprinosi poboljšanju prognoza tuče i munja za javnost, ali i specifične korisnike (npr. energetski sektor, promet, poljoprivreda...). S druge strane, dobiveni rezultati otvaraju mogućnost za analizu učestalosti i obilježja tuče u budućoj klimi što izravno doprinosi stvaranju budućih prijedloga prilagodbe klimatskim promjenama.

Extended abstract:
1. Introduction

Hail is a severe weather hazard that can produce significant crop and property damage across the world (Allen et al., 2020), especially when it occurs over highly populated areas with high-density assets (Kunz et al., 2018). In the literature, a large number of even individual hailstorms causing more than US$1 billion in damage is reported across the world (Schuster et al., 2005; Changnon, 2009; Brown et al., 2015; Kunz et al., 2018; Púcik et al., 2019). As described by Punge and Kunz (2016) and Púcik et al. (2019), several hail hotspots can be found in Europe, including the pre-Alpine and Adriatic areas. Although large hail occurs less often over the highest mountain peaks in the central Alps, severe hailstorms frequently affect Switzerland with up to 4 large hail days per year (Nisi et al., 2016; Púcik et al., 2019). In this area, the maximum hail diameter can sometimes exceed 10 cm (e.g. see Figure 8 from Púčik et al., 2019). Furthermore, parts of Croatia (Počakal et al., 2018; Jelić et al., 2020a) and broader northern Adriatic region (e.g. Manzato (2012)) have similar statistics of hail frequency as southern Germany or south-eastern Austria (Punge and Kunz, 2016). Therefore, considering the high economic losses associated with (severe) hailstorms, and high frequencies of hail occurrence, it is very important to have reliable hail forecasts, both for short-term numerical weather prediction and long-term climate-change adaptation strategies.

One of the largest limitations in understanding processes involved in hail formation is the lack of dense and direct measurements of hail properties on the ground. Hailpads, which are simple meteorological devices consisting of a stand and a measuring plate, represent one of the few methods to detect and measure hailstones directly on the ground. Besides the number of falling hailstones and their diameters, hailpads can also detect the intensity (i.e. kinetic energy) of hail (Smith i Waldvogel, 1989). In Europe, hailpad networks exist in several regions including parts of Spain, France, Greece, northern Italy, eastern Austria and parts of Croatia (Svabik, 1989; Dessens, 1998; Giaiotti et al., 2003; Sioutas et al., 2009; Počakal et al., 2009; Berthet et al., 2011; Počakal, 2011) and have also been used in randomized hail suppression experiments in Switzerland (Federer et al., 1978). Although hailpads are one of the few sources of direct information on hail occurrence, they provide spatially discrete (but unique) information on hail occurrence as they only record hail at the point where they are installed.

Another source of information on hail occurrence is related to weather radars. As the abilities of weather radars to detect different kinds of hydrometeors such as rain, snow and hail progressed over the years, several hail detection algorithms have been developed (e.g. Waldvogel et al., 1979; Witt et al., 1998). At the present, hail detection algorithms are widely used as hail proxies and can provide spatially continuous information on various hail properties, e.g. probability of hail occurrence or maximum expected hailstone size. In Switzerland, two hail detection algorithms are operational in real-time, namely, Probability of Hail (POH, Waldvogel et al., 1979; Foote et al., 2005) that indicates a probability of a hailstorm occurring at a certain location, and Maximum Expected Severe Hail Size (MESHS, Treloar, 1998; Joe et al., 2004) that estimates expected severe hail size at the ground over the Alpine region.

An additional challenge in understanding hail processes is the limited number of high-resolution modelling studies of hailstorms. With increasing computational power, it has become possible to run simulations at convection-permitting scales (horizontal grid spacing < 4 km). Several studies reported the benefits of using models at kilometre scales for more realistic representations of convective processes (Leutwyler et al., 2017), mean diurnal cycles of precipitation (Ban et al., 2014a), spatial precipitation patterns and associated extreme values (Prein et al., 2013; Brisson, Van Weverberg, et al., 2016; Brisson et al., 2018; Fowler et al., 2021; Pichelli et al., 2021), better representation of convective clouds (Keller et al., 2016; Brisson, Van Weverberg, et al., 2016; Hentgen et al., 2019), local wind systems like sea breeze (Belušić et al., 2018), and complex terrain winds (Horvath et al., 2012). Since models, when run at km scales, can produce a more realistic representation of convective processes, Adams-Selin and Ziegler (2016) integrated a physically improved 1D hail growth scheme – called HAILCAST (Poolman, 1992; Brimelow et al., 2002; Jewell and Brimelow, 2009) – with the km-scale WRF model. When HAILCAST is coupled with WRF, the model simulates the maximum expected hail size at the ground using the profiles of cloud liquid and ice water, vertical velocity, temperature, water vapor and pressure fields from a given model timestep. Several recent studies employed HAILCAST embedded in high-resolution numerical models, such as WRF or COSMO, to study hailstorms occurring over the United States and parts of Europe. The studies found that the models can reproduce the atmospheric conditions and triggering mechanisms responsible for hailstorm formation, resulting in simulating comparable hailstorms to those observed over the complex terrain of the United States (Adams-Selin and Ziegler, 2016; Adams-Selin et al., 2019), Switzerland (Trefalt et al., 2018; Raupach et al., 2021; Cui et al., 2023), and Italy (Manzato et al., 2020; Tiesi et al., 2022).

Similar to hail, lightning poses a serious threat to human lives (Curran et al., 2000; Holle et al., 2005), wind turbines (Rachidi et al., 2008) and transportation (Kanata et al., 2012; Lee and Collins, 2017; Thornton et al., 2017). Moreover, lighting is a major cause of wildfires (Latham and Williams, 2001; Abatzoglou and Williams, 2016; Dowdy et al., 2017). Considering the hazards associated with lightning occurrence, the lightning potential index (LPI) was developed as a tool for diagnosing areas prone to lightning discharges (Lynn and Yair, 2008; Yair et al., 2010). With a better representation of convective processes km-scale simulations, LPI offers the possibility to use the parameterizations of lightning that describe the non-inductive process occurring inside a thundercloud (Yair et al., 2010; Brisson et al., 2021). It is defined as a potential for charge formation and separation inside a thundercloud and it relies on the presence of both solid and liquid hydrometeors. Even though LPI is not directly connected to the observed number of lightning flashes, several studies found that LPI could be a valuable tool for implicit lightning forecasting in COSMO (Sokol and Minářová, 2020, Cui et al., 2023) and WRF (Yair et al., 2010; Lagasio et al., 2017a) models. Recently, LPI was used in the climatological assessment of lightning over Germany (Brisson et al., 2021) and proved to be a better indicator of lightning occurrence than the commonly used convective available potential energy times precipitation (CAPE x PREC) parameterization (Romps et al., 2014).

In this context, the aim of this research is to investigate the predictive ability of the mesoscale WRF and COSMO models in simulating atmospheric conditions leading to hail and lightning occurrence, but also examine the ability of HAICLAST and LPI diagnostics in reproducing the characteristics of hail and lightning during storms over the Alpine-Adriatic region with a special focus on Croatia. Furthermore, using the WRF model alongside HAILCAST and LPI, the conditions present during the occurrence of (early) morning hail in Istria will be investigated. Specifically, the aims of this study can be summarized as:

I. Evaluation of WRF-HAILCAST and LPI results in simulation of observed characteristics of hail and lightning during several selected hail cases over Croatia. Sensitivity tests of results on the choice of planetary boundary layer (PBL) and microphysics parameterization schemes.

II. Comparison of COSMO and WRF results in simulating hailstorms over the Alpine-Adriatic region.

III. Investigation of the atmospheric conditions during the occurrence of early morning hail in Istria.

2. Data and methods

Within this study several datasets were used to evaluate the numerical simulations. Firstly, the model's ability to reproduce general surface conditions on the selected hail days using standard meteorological measurements from automatic stations maintained by the Croatian Meteorological and Hydrological Service (DHMZ). We used hourly values of temperature, relative humidity and hourly maximum wind speed from the stations across Croatia. The surface conditions are evaluated using the RMSE decomposition methods.

For the evaluation of precipitation, the Final Run of Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) mission (Huffman et al., 2019) dataset is used. IMERG is a globally gridded precipitation product that estimates surface precipitation rates at 0.1° spatial and 30 min temporal resolution. IMERG incorporates satellite microwave precipitation estimates, microwave-calibrated infrared satellite estimates and rain gauge observations. To evaluate the precipitation, Taylor diagrams are used.

To assess the ability of LPI to reproduce the observed lightning activity, lightning data from the Lightning Detection Network (LINET) (Betz et al., 2009) is used. Here, we considered total lightning information, i.e., we did not differentiate between types or polarities of lightning flashes as LPI presents the overall potential for lightning activity without distinction to the type or polarity of lightning discharges. The total lightning for the examined cases was taken from the 2D database of lightning flashes at a 3 km x 3 km horizontal and 2 min temporal resolution (developed by Jelić et al., 2021). LPI is assessed against LINET measurements using the minimum coverage neighbourhood verification method as well as the object-based Structure-Amplitude-Location (SAL) verification method.

Next, hail detection products from the Swiss radar network (Germann et al., 2015; Willemse and Furger, 2016) operated by MeteoSwiss are used to assess the HAILCAST results. Namely, operationally computed probability of hail (POH) product is used. POH indicates the gridbased probability of hail reaching the ground. Similar to evaluating lightning, a minimum coverage neighbourhood verification method is used.

Finally, HAILCAST results are assessed against direct hail measurements from the Croatian hailpad network. It consists of (i) hail suppression stations in the continental region of Croatia, (ii) a specially designed hailpad polygon in north-western Croatia, and (iii) hailpad stations in the north-eastern (NE) Adriatic region. Here, a proposed upscaled neighbourhood verification method is used to evaluate HAILCAST results against hailpad measurements.

3. Results and conclusion

The current study presents an analysis of the capabilities of recently developed diagnostic tools for the simulation of hail and lightning, specifically HAILCAST and LPI. These diagnostic tools were used for the first time over Croatia, but also over the wider Alpine-Adriatic region. Moreover, the hail simulations were evaluated, for the first time, using direct hail measurements on the ground. A systematic analysis and evaluation of the results was carried out both in the regime of short-term weather forecasts and in the regime of climate simulations. The conducted doctoral research represents an important scientific contribution to the improvement of weather forecasts and climate simulations of extreme weather with an emphasis on hail and lightning through:

i. Detailed statistical and dynamic evaluation of simulated atmospheric conditions present during selected cases of hail over the wider Alpine-Adriatic area. Quantifying the performance of current mesoscale numerical models in simulating the present atmospheric conditions during selected hailstorms.

ii. A detailed statistical and dynamic evaluation of diagnostic tools for the simulation of hail and lightning over the wider Alpine-Adriatic area. An analysis of the advantages/disadvantages of the selected diagnostic tools was carried out, as well as the sensitivity of the results to the choice of mesoscale model and settings within one model. This represents the first attempt in Croatia, and one of the few in Europe, to use diagnostic tools such as HAILCAST and LPI for the purpose of simulating the observed characteristics of hail and lightning and their systematic and detailed evaluation.

iii. Analysis of the atmospheric conditions during early morning convection, with an emphasis on hail, over Istria. Statistical and dynamical evaluation of the mesoscale numerical model in the simulation of the atmospheric conditions during the occurrence of early morning hail along with the evaluation of diagnostic tools in the simulation of hail and lightning. This directly contributes to the understanding of the conditions under which early morning hail occurs in Istria, which could lead to better forecasts of early morning convection.

Therefore, the main results obtained within the presented doctoral research can be summarized as:

i. Current mesoscale models can reliably reproduce the atmospheric conditions present during the occurrence of hail in Croatia, but also in the wider Alpine-Adriatic region.

ii. Diagnostic tools for the simulation of hail and lightning show promising results in simulating the observed characteristics of hail and lightning over Croatia, but also the wider Alpine-Adriatic region. The selected diagnostic tools are successful in simulating the spatial characteristics and intensity of observed lightning activity. Similarly, good performance was found in the simulation of the spatial characteristics of hail measured by radar products from Switzerland and the network of hail gauges from Croatia. The variability of the results in the selection of the mesoscale model and settings within one model indicates the benefit of using a multimodel and/or multiphysics ensemble when simulating these events.

iii. It was established that early morning hail over Istria mostly occurs in cyclonic weather types. In addition to synoptic conditions, mesoscale and local conditions also play an important role in the formation of convection and hail. Current models show good performance in simulating selected events.

The obtained results are promising and indicate that the analysed diagnostic tools could be a valuable contribution to the operational forecast of hail and lightning, but also to the climate assessment of the occurrence of hail and lightning in the current and future climate. This directly contributes to the improvement of hail and lightning forecasts for the public, but also for specific users (e.g. energy sector, transport, agriculture...). On the other hand, the obtained results open up the possibility to analyse the frequency and characteristics of hail in the future climate, which directly contributes to the creation of future climate change adaptation plans.