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The behavior of the radar parameters of cumulonimbus clouds during cloud seeding with AgI

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ABSTRACT

Deep convection yielding severe weather phenomena (hail, flash floods, thunder) is frequent in Serbia during the warmer part of the year, i.e. April to September. As an effort to mitigate any potential damage to material goods, agricultural crops and vegetation from larger hailstones, cloud seeding is performed. In this paper, we analyzed 29 severe hailstorms seeded by silver iodide. From these, we chose five intense summer thunderstorm cells to analyze in detail the influence of silver-iodide cloud seeding on the radar parameters. Four of them were seeded and one was not. We also used data from firing stations (hail fall occurrence, the size of the hailstones). The most sensitive radar parameter in seeding was the height where maximum reflectivity in the cloud was observed. Its cascade appeared in every case of seeding, but was absent from the non-seeded case. In the case of the supercell, increase and decrease of the height where maximum reflectivity in the cloud was observed occurred in almost regular intervals, 12 to 15 min. The most inert parameter in seeding was maximum radar reflectivity. It changed one to two dBz during one cycle. The height of the top of the cloud and the height of the zone exhibiting enhanced radar echo both had similar behavior. It seems that both increased after seeding due to a dynamic effect: upward currents increasing due to the release of latent heat during the freezing of supercooled droplets. Mean values of the height where maximum reflectivity in the cloud was observed, the height of the top of the cloud and the height of the zone exhibiting enhanced radar echo during seeded period were greater than during unseeded period in 75.9%, 72.4% and 79.3% cases, respectively. This is because the values of the chosen storm parameters were higher when the seeding started, and then those values decreased after the seeded was conducted.

1. Introduction

"Weather modification is one of those areas in which science can have an immediate and obvious benefit for society" (Nature, 2008). Cloud seeding with AgI has been studied for a long time, with focuses on both hail suppression and rain enhancement (Bruintjes, 1999; Guo et al., 2006; Zipori et al., 2012; Potapov and Garaba, 2016). The main goal of hail suppression is to decrease the frequency of hail occurrences or to decrease the diameter of hailstones and thereby mitigate any potential damage to crops, cars and other material goods. Hail suppression in Serbia is based on the Soviet concept of seeding (Sulakvelidze, 1967) where silver iodide (AgI) is directly injected using rockets. The AgI reagent is seeded in the temperature zone −4 °C to −12 °C between the radar reflectivity contours of 15 and 45 dBz, at frequent zone about 5000 m. This concept relies on the following: by seeding hail bearing clouds with AgI nuclei, the number of potential deposition nuclei increases (taking into account both naturally occurring nuclei and AgI). This induces competition for any available supercooled water. The objective is for a larger number of smaller hail particles to form, thereby preventing the formation of large hailstones. These smaller hailstones then melt completely or partially under the cloud's base, in a region of positive temperatures. Using this method, potential hail damage could be significantly reduced. This method is used in many countries across the world (Abshaev, 1999). Hail suppression systems work if seeding is done early on in a cloud's life and if enough seeding material is within its boundary layer (Dessens et al., 2016). The seeding methodology depends on the type of clouds involved. Aleksić (1989) describes this in detail.

Forecasts of any potential hail precipitation are important for the success of hail suppression technology. However, forecasting the exact time, location and intensity of hailstorms is a complex task that still exceeds present theoretical, modeling and computational capabilities (Garcia-Ortega et al., 2011). Numerical models often cannot predict hail (or rain) from a thunderstorm due to their small spatial and temporal scale, which are under model's resolution. Vujović et al. (2015) proposed threshold values for stability indices with the highest potential for accurate thunderstorm forecasting in the Belgrade region. They concluded that latent instability (measured by lifted index and Showalter index) and potential instability (measured by total totals index and K

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index) are the most important conditions to take into account for the accurate forecasting of an imminent thunderstorm in the Belgrade region. If threshold values of these indices are surpassed, possible Cumulonimbus clouds development is forecasted. However, as Merino et al. (2014) stated, "there are many factors that cannot be analyzed based on instability indices but are of great importance in the formation of hailstones, as well as other factors that explain the triggering of convection".

A number of numerical studies concerning cloud seeding have been conducted in Serbia. Aleksić et al. (1992) analyzed the transport and diffusion of a reagent in a two-dimensional, non-hydrostatic numerical model. The reagent is seeded in the layer (−6 °C to −12 °C) between radar reflectivity contours of 25 and 45 dBz. The height of this layer depends on the period of the year. They concluded that direct injection seeding using rockets should be performed almost continuously and, in any case, in intervals not exceeding a few minutes. Vučković (2003) implemented the mixing ratio of the reagent as a prognostic variable in a sophisticated three-dimensional cloud-resolving model. He also designated and implemented a scheme for seeding into the model, which included determining a zone for seeding. He concluded that the accretion of cloud water by hail in the dry regime of growth and the accretion of rainwater by snow are the most significant mechanisms for decreasing hail production by seeding, and that melting hail is responsible for an increase in rainwater. Ćurić et al. (2006) researched the dispersion of the seeding agent. According to their findings, seeding under the base of the cloud is not a good solution and they concluded that a seeding area must be selected depending on internal cloud dynamics. By conducting numerical simulations, Ćurić et al. (2007) found that if a seeding zone in the form of a circular sector is seeded at an early stage of cloud development and with a large amount of seeding agent, the amount of hail accumulated at the surface is significantly reduced (by 6.61%) and rain precipitations increased (by 8.43%). The seeding zone in this sensitivity test was in the layer (−5 °C to −15 °C) at the height of about 5000 m bounded by the reflectivity of 1 and 65 dBz. The lateral edges of the circular sector were at the angles of 90° and 30° right and left, respectively, of the movement of the storm.

The assessment of hail suppression is important. However, it complicates the problem from a practical point of view. Namely, natural variability can mask results from randomized cloud seeding (WMM, 2015). As Dessens et al. (2016) specified, rocket seeding is very successful in Russia (Abshaev and Malkarova, 2003; Tlisov and Khuchunaev, 2003). In Serbia, where the Soviet method is used, rocket seeding has been shown to be successful as well (Mesinger and Mesinger, 1992; Vujović et al., 2007).

In Serbia, hail suppression has been in use since 1967, over a territory of 77,498 km^2. Every year, this system is in operation from April 15 through October 15. Hail rarely occurs in Serbia between November and March. Aleksić et al. (1989) concluded, "Hail suppression season in Serbia has the proper starting date, but there is a strong possibility that the season could be ended earlier". The operational system consists of 13 radar centers equipped with S-band radars, 1800 launching stations, and a radio communication system composed of 50 repeaters and 1800 radios and, finally, an operational and methodological center in Belgrade (Vujović et al., 2007). Ten radar centers equipped with Mitsubishi RC 34A radars, and three with Gematronik Meteor 400 SLP13 radars. Some technical specifications of the radar and the launching stations used at the Radar center "Užice" whose data are used in this study are given in the Appendix A. The launching stations are evenly distributed over the entirety of the designated territory, with a distance of approximately 5 km between stations. Each rocket contains 0.4 kg of a pyrotechnic mixture containing approximately 8% AgI. The lowest amount of active particles per gram of silver iodide is 10^{12} at −6 °C (Vinča, 1985). The largest AgI particles are effective at −5 °C, while smaller particles are effective at lower temperatures (Dessens et al., 2016). Rančić et al. (1997, 1999) developed the software HASIS (Hail Suppression Information System), in order to be able to visualize the seeding process and determine the elements of rocket launching. The procedure is as follows. The radar center receives a weather forecast every day from the Republic Hydrometeorological Service of Serbia (RHMZ). If the weather forecast foresees cumulonimbus (Cb) development on that particular day, the radar center informs the personnel at the launching station to remain and be prepared to fire the rockets if convection reaches a critical level. When the seeding criteria that are given in the next section are fulfilled, the HASIS system at the radar center determines the elements of rocket. These elements are then forwarded to the launching personnel. If seeding is unsuccessful, another round of seeding is carried out within a period of 5 min or less (in accordance with the findings of Aleksić et al. (1992)). The time intervals between definitive approval regarding whether to continue firing or not should not exceed two minutes.

As it was shown, many numerical studies of cloud seeding have been conducted in order to more thoroughly research the seeding process. Nevertheless, the behavior of radar parameters after seeding was not considered. Therefore, the objective of this paper is to study the impact of cloud seeding via the injection of AgI on radar parameters in summer cumulonimbus clouds. The summer means the warm part of year (i.e. April to September). The method is described in Section 2. Results and discussion are given in Section 3. The findings are summarized in Section 4.

2. Data and methodology

Mixed clouds that consist of liquid water and ice particles are suitable for seeding using AgI, due to the participation of AgI in the Bergeron-Findeinsen process. Seeding can have an influence on the microphysics (glaciations) of a cloud or influence cloud dynamics (the intensification of updraft, the rising of a cloud's top height, and alteration of a cloud's lifetime). The following conceptual representations and methodological principles for hail modification used in practice are derived from the results of numerical and experimental studies and long-term empirical experience at the Republic Hydrometeorological Service of Serbia (part of which is the Hail Suppression Department). The meteorological radar measures the following characteristics of convective cells:

N_{max} – the maximum value of radar reflectivity,

H_{nmax} – the height where maximum reflectivity in cloud was observed,

H_{vz} – the height of the zone exhibiting enhanced radar echo; this zone is defined as a volume of the cloud where radar reflectivity is ≥45 dBz (bordered by the isosurface of 45 dBz),

D45 – the diameter of the zone exhibiting enhanced radar echo, i.e. diameter of the zone bordered by the isosurface of 45 dBz,

H_v – the height of the top of the cloud, and

DR – the thickness of the ring on PPI at the level of −6 °C bordered by isosurfaces of radar reflectivity of 15 and 45 dBz.

These variables are known as the radar parameters. Based on their values, we estimate the intensity of convection and make a decision as to whether or not we seed a particular cloud. Four seeding criteria should be fulfilled before seeding commences:

1. Maximum radar reflectivity should be >45 dBz (N_{max} > 45 dBz). Areas with maximum radar reflectivity indicate locations where hail exists, as the intensity of the return radar echo depends on the concentration of, and even more so the dimension of, hydrometeors.
2. The height of maximum radar reflectivity should be greater than the height of the zero isotherm ($H_{nmax} > H_{0\ °C}$). During a cloud's growth stage or in an early phase of a cloud's mature stage, N_{max} is observed above the maximum of upward motion. Therefore, H_{nmax} is a good indicator of how strong its vertical velocity is and where its position is.