Summary of the research

(i) The earlier version of our the bin microphysical scheme (University of Pecs and NCAR Bin scheme, hereafter UPNB) implemented into WRF NWP model was modified to simulate the impact of artificially injected AgI particles on the precipitation formation. (Applicability of the UPNB scheme was presented in a paper published in 2017 in the **Monthly Weather Review**.) This new version of the model allows us to simulate how the artificial enhancement of the concentration of ice forming nuclei affects the precipitation formation in winter orographic clouds. The research about the study of seeding effect in wintertime orographic clouds was completed during this research project. Two papers were published about the results. In the paper published in **Journal of Applied Meteorology and Climatology (JAMC)** in 2017 the impact of AgI seeding on the precipitation formation in the clouds formed over an idealized 2D bell shape mountain was studied. The results about this numerical experiment are summarized as follows:

(a) The efficiency of seeding depends on the cloud type, microphysical characteristics of the cloud (e.g. concentration of cloud condensation nuclei (CCN), and that of naturel ice forming nuclei (IN)) and location of seeding.

(b) While the seeding increases the amount of surface precipitation in most of the cases in the orographic layer clouds, the amount of the surface precipitation may be reduced due to the seeding in the case of convective clouds.

(c) The artificial seeding has a significant impact on the spatial pattern of the surface precipitation. Even if the seeding enhances the surface precipitation on the windward side of the mountains, the amount of the surface precipitation is frequently reduced on the lee side of the mountains.

The results about numerical simulation of real cases of Wyoming Winter Weather Modification Project (WWWMP) were published in **JAMC** in 2020. The 3D version of the WRF NWP model was used to simulate the impact of the AgI seeding on the precipitation formation at different atmospheric conditions (four different soundings and different concentrations of CCN and IN). The results are summarized as follows:

a) The efficiency of seeding strongly depends on the environmental conditions and cloud microphysical properties. Our results suggest that in the case of orographic winter clouds the h-LWP (horizontally integrated liquid water content) can be a reasonable parameter for the estimation of the seedability.

b) The efficiency of seeding is inversely correlated to the efficiency of precipitation formation in natural case and it has a strong correlation with enhancement of diffusional growth of snowflakes due to the seeding.

c) Our result shows that the seeding effect is between 0 and 7% depending on the simulated cases. This result does not contradict to the efficiency of 5% evaluated on the base of the comparison of the snowfall over the target and control areas in WWWMP

(ii) A novel, detailed microphysics scheme was developed to simulate, how the hygroscopic seeding material can impact the precipitation formation at different environmental conditions.

The novelty of this hybrid bin scheme is that it allows to simulate both the diffusional growth in undersaturated environment where the effect of the curvature and solution terms is significant, and as well as the collision – coalescence above the cloud base. This study is related to two weather modification filed projects. One of the seeding projects occurred near to the east coastal area in Australia, the other one was in United Arab Emirates. During these projects the characteristics of the background aerosol particles and seeding materials were observed. These data were used to perform a sensitivity test to find relation between the microphysical characteristics of the clouds and the efficiency of seeding. The results are as follows:

(a) While the early broadening of the drop size distribution is sensitive on the presence of the coarse particles if the updraft is weak (about 1 m s^{-1}), in the case of the severe convective clouds (updraft velocity at the cloud base is 5 m s^{-1}, or larger) the evolution of the size distribution of water drops does not depend on the characteristics (concentration and hygroscopicity) of the coarse particles. In the case of weak updraft the small supersaturation and the presence of coarse particles (depending on their hygroscopicity) enhance the Ostwald-ripening effect, which can significantly impact the evolution of the droplet size distribution (DSD hereafter) near the cloud base. When the updraft at the cloud base is strong (≈ 5 m s^{-1}), background, coarse particles do not play important role in broadening of the DSD even if there concentration is high (≈ 5 cm^{-3}).

(b) The hygroscopic seeding can be efficient if the uptake the vapor below the cloud base by seeding material effective. However, the seeding can have a negative effect (reduces the precipitation) if the concentration of the seeding material is too high, and size of the seeding particle is comparable with the size of natural, fine aerosol particles.

(c) The efficient vapor uptake by the coarse, highly hygroscopic aerosol particle can result in superadaibatic liquid water content above the cloud base. In the line with field observation our numerical simulation shows that superadaiabatic liquid water content can evolve if the updraft velocity is weak (1 m s^{-1}) at the cloud base.

The manuscript contains these results have been accepted in the **Atmospheric Chemistry and Physics** and it will be published in 2021 or in 2022.

(iii) As a part of an international collaboration (*Chinese Academy of Meteorological Sciences*, *National Center for Atmospheric Research* and *University of Pécs*) the microphysical background of the charge separation in the thunderstorms has been studied. The equations about the charge separation in convective clouds were implemented into our numerical microphysical model (UPNB). This new scheme was used to study how the charge separation occur in different regions of the squall lines. There are numbers of hypothesis about the processes play role in the charge separation. In this research the role of the liquid layer formed on melting solid particles (snowflakes and graupel particles) was studied. The main finding was that the charging mechanism in the melted layer formed on snowflakes resulted in a major, positively charged layer below 0°C isotherm in the stratiform regions, furthermore the charging process relates to graupel melting enhanced the lower positively charged layer in the convective regions. This result gives an explanation on the formation of the wide, positively charged layer have been frequently observed in the stratiform region. The results was published in the **Journal of Geophysical Research Letters** in 2020.

(iv) The piggybacking approach is a useful, recently developed technique which helps to separate dynamical and microphysical impact on cloud formation. Due to the complexity of this method only numerical models with bulk microphysical schemes have been applied for this purpose. Implementing our bin microphysics (UPNB) scheme significantly extends the scale of the applicability of this technique. Two idealized cases have been selected for the demonstration of the piggybacking potential. The first one is an idealized 3D squall line case, the second case is a daytime convection development over land. The summary of the results is:

a) For the squall line case, the results of bin scheme are compared with that of one of the standard bulk schemes available in WRF. The results suggest that the transition zone (zone between the stratiform and convective regions) in the squall line originates from the microphysics-dynamics coupling, and not microphysics alone.

b) For the daytime convection case, the UPNB scheme is applied into simulate differences between convections developing in pristine and polluted environments. The piggybacking approach clearly demonstrates that surface rain accumulations must come from differences in the flow simulated by the two different CCN concentration.

The manuscript summarizing these results have been recently submitted to **JAMES (Journal of Advances in Modeling Earth Systems).**