OPTIMIZATION OF AEROSOL SEEDING IN RAIN ENHANCEMENT STRATEGIES (OASIS)

Final Report

UAE Research Program for Rain Enhancement Science

Reporting Period (Interim January Report) **(PLEASE FILL IN THE INFORMATION BELOW)**	
Start Date	***1.1.2020***
End Date	***31.8.2020***
Submittal Date	***15.9.2020***
Finnish Meteorological Institute	
Principal Investigator	Prof. Hannele Korhonen

EXECUTIVE SUMMARY

All project milestones and deliverables have been successfully completed. Further analysis of data as well as preparation of several manuscripts continues.

The main results of WP1 as well as Tasks 2.1 and 2.3 were listed in previous reports. In Task 2.2 the cloud-scale simulations were completed during spring 2020, spanning multiple sensitivity tests on background aerosol and boundary layer moisture. The model data indicated the importance of mixed-phase microphysics and riming in mediating the effect from hygroscopic seeding to precipitation. Based on the cloud-scale simulations, WP3 concentrated on identification of most favorable cloud seeding conditions with the help of statistical AI methods. We employed convolutional neural networks with the aim of predicting the rime fraction of the in-cloud hydrometeors and using this parameter to predict the most promising seeding conditions.

Based on the whole project, our main conclusions regarding operational weather modification are: 1) Informed cloud seeding will require simultaneous forecasting of vertical profiles of clouds, aerosol, winds and humidity. This information can be provided by a combination of ground-based remote sensing, satellite measurements and well-evaluated numerical weather prediction (ensemble-based). 2) Mixed-phase microphysics (e.g. the riming process) plays a key role in efficient hygroscopic seeding of UAE convective clouds. The neural network approach developed for identifying the cloud rime fraction shows promise in predicting favorable seeding conditions, but in order to construct an operational forecasting tool, a more comprehensive mapping of different atmospheric conditions and a dedicated research project is required. 3) Ice nucleation activity of silver iodide (AgI) can potentially be enhanced via specific microscopic surface structures. The feasibility of manufacturing such particles depends on the advances in and cost of experimental manufacturing processes.

SCIENTIFIC AND TECHNICAL PROGRESS

Overall scientific and technical progress

All project deliverables have now been fully completed. During the 6-month project extension, the work focused on Task 2.2 (cloud-scale simulations) and WP3 (identification of conditions for clouds susceptible to seeding).

Summary of technical activities and results from major project tasks during reporting period

Task 2.2 Cloud-scale modelling: (lead Prof. Sami Romakkaniemi)

During the reporting period, the focus of Task 2.2 has been to run and complete a set of experiments of cloud seeding, targeting the summertime convective clouds over the UAE. The input parameters for the simulated case were obtained from the NWP simulations performed in Task 2.1 earlier in the project, as well as from the field measurements conducted in WP1. The ambient aerosol concentration was measured directly only close to the surface. Using Lidar-backscatter profiles to infer the approximate vertical distribution of the aerosol, the surface concentrations were scaled within the boundary-layer and in the free troposphere. This scaling was fitted to be consistent with the thermodynamical stratification of the atmosphere in the simulated case.

Several sensitivity experiments were conducted, where the effect of reducing the background aerosol concentration and modifying the boundary layer moisture content were tested. In general, the results highlighted the importance of mixed-phase processes and, in particular, riming in controlling the overall rainfall, which in itself is not a surprising result. However, the seeding experiments, using hygroscopic particles as the seeding agent, indicated that most of the rain enhancement also came from changes in the mixed-phase processes and riming. It was noted that rime fraction carries some information about the seedability of the cloud. For example, reducing the ambient aerosol resulted in overall higher precipitation rates, which were associated with higher rime fractions, but the rain enhancement from seeding was reduced. This suggests that heavily precipitating events with efficient riming within the cloud are not very susceptible to hygroscopic seeding, whereas higher susceptibility was seen with weaker precipitation events and moderate riming. However, we also noted that changing boundary-layer moisture modifies the apparent relationship between the rime fraction and cloud seedability, which reveals the complexity of the issue and shows that any single parameter alone is most likely insufficient as an indicator for seedability.

The main researcher working in this task was Dr Juha Tonttila, supervised by Dr Sami Romakkaniemi.

WP3 Statistical analysis (leads: Prof. Hannele Korhonen and Prof. Miikka Dal Maso):

After consultation with NCM and the SDG in November/December 2019, the focus of WP3 was shifted to identification of most favorable cloud seeding conditions with the help of statistical AI methods.

In the first phase, cloud water mixing ratio and vertical velocity fields were extracted from a set of UCLALES-SALSA simulations. These fields were used as input to the *tobac* algorithm (Heikenfeld et al., 2019), which performed the detection, tracking and segmentation of convective clouds from the model simulations. The detection of cloud features at each time step was based on finding the horizontal locations of maximum vertical velocity between 3-10 km. Three-dimensional cloud segments were extracted using a watershed algorithm, which operates on the target quantity and selects those grid boxes in which cloud water mixing ratio is above a user-defined threshold.

After the cloud segments were delineated from the model data, summary statistics and vertical profiles were calculated for a set of atmospheric and aerosol quantities over the cloud segments. Multiple UCLALES-SALSA simulations run with varying thermodynamic conditions as well as aerosol properties were included in order to capture the effect variations in background conditions on simulated rime fraction. A separate set of LES simulations was also carried out to provide semi-independent data for validation.

Subsequently, the main aim was to assess to what extent the rain enhancement potential of mature clouds could be predicted using machine learning if atmospheric conditions and aerosol properties were known at the cloud initial stage. For each cloud, the input data was selected from that time step where the cloud was detected for the first time. Predictions for cloud seedability were made for the time the target cloud obtained its maximum depth.

As it is very difficult to quantify rain enhancement potential based on a single realization, rime fraction was used as the target variable in the machine learning exercise, as it was suggested as a possible indicator by the results from Task 2.2. Predictions were made with a convolutional neural network (cnn), using the UCLALES-SALSA simulations as training data. The results showed that cnn is able to capture the cloud-to-cloud variation of the average rime fraction. Even for separately conducted validation simulations (different realizations, but with boundary conditions identical to the training dataset), the general behavior of average rime fraction from one simulation setup to another is captured well. Furthermore, the vertical profile of rime fraction reasonably was also captured well on average, although for some individual clouds the results are poorer.

All in all, these results indicate the developed approach holds potential for further development aiming at forecasting the efficiency of seeding in different meteorological conditions for operational purposes. However, development of such tool would be a separate research project of its own. Further research is needed on what are the most important features in the input data that explain the good performance of cnn when modeling the overall vertical profile of rime fraction and whether these results generalize to other models or different atmospheric conditions. The current conclusions hold only for the tested UCLALES-SALSA simulations, and it is not automatically warranted that neural networks would perform equally well in real-world cases.

During the 6-month extension, the work was carried out by Dr Olle Räty (FMI) and was supervised by Prof. Hannele Korhonen, Prof. Sami Romakkaniemi and Dr Juha Tonttila.

KEY CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Here we summarize our key conclusions in terms of cloud seeding operations, as well as make some recommendations for future work. A more complete description of the project's scientific findings is given in Appendix 1 at the end of this document.

Based on our 1-year field campaign, operational weather modification activities will require adequate forecasting of all following vertical profiles: clouds, aerosol, winds and humidity. The winds measured at the surface are not representative of the winds aloft, and the ambient aerosol concentrations and characteristics at different altitudes show a strong dependence on source direction. The latter is important as our cloud-scale model simulations highlight the key role of cloud-level aerosol concentration in determining cloud rime fraction and therefore its susceptibility to seeding. Furthermore, the field campaign showed that most clouds that have potential for rain generation form at quite high altitudes, above the top of the convective boundary layer, and reside typically above a very dry layer 1-2 km thick, which will cause strong evaporation of the precipitation falling through. Knowledge of the atmospheric humidity profile is therefore key to successful rain enhancement activities, as even if cloud seeding conditions are optimal, a dry atmosphere below will substantially reduce the precipitation reaching the surface.

The required information on vertical profiles necessary for informed cloud seeding can be provided by a combination of ground-based remote sensing, satellite and numerical weather prediction. Based on our numerical weather prediction simulations we conclude that the value of such forecasts should be optimally established in actual trials. Ideally, an ensemble prediction system should be used to produce probabilistic forecasts of seeding-potential, including a quantitative measure of the uncertainty of each forecast. The optimal usage of available observations as well as optimal ways to generate spread in the ensembles are crucial subjects in need of further study.

Our cloud-scale numerical simulations underline the importance of mixed-phase microphysics (e.g. riming) in determining the success of hygroscopic seeding in the UAE convective clouds. Further investigation into the mixed-phase processing in the context of cloud seeding is needed, including with modelling methods leaning more towards NWP, although a detailed description of the aerosol-cloud microphysics remains as a prerequisite. Such an approach could allow a more comprehensive mapping of different atmospheric conditions; at the present, the computational cost of our detailed cloud-scale model makes very large simulation ensembles impractical.

A neural network approach developed during the project was shown to have good skill in identifying conditions that, at least in a limited set of computationally heavy cloud-scale simulations, have potential for successful rain enhancement. For example, increase in background aerosol concentration, which typically decreases the overall surface precipitation, tends to lead to relatively more efficient seeding. The neural network approach therefore shows potential to serve as a basis upon which a future forecasting tool could be developed with the aim to forecast the seeding success in different ambient meteorological conditions for operational purposes. Development of such an operational tool will, however, require a dedicated research project as well as the type of comprehensive mapping of atmospheric conditions outlined in the previous paragraph.

Our molecular scale simulations indicate that specific surface structures or defects can substantially enhance ice nucleation, even on already very active silver iodide (AgI) surfaces. Provided experimental modification of particle microscopic surface structures will further advance in accuracy and prove cost-effective, this finding could enable manufacturing of artificial particles that nucleate ice at nearly zero supercooling.

PUBLICATIONS/PRESENTATIONS

Peer-reviewed publications

Published

Callewaert S., S. Vandenbussche, N. Kumps, A. Kylling, X. Shang, M. Komppula, P. Goloub and M. De Mazière, *The Mineral Aerosol Profiling from Infrared Radiances (MAPIR) algorithm: version 4.1 description and evaluation*, Atmos. Meas. Tech., 12, 3673-3698, https://doi.org/10.5194/amt-12-3673-2019.

Filioglou, M., Giannakaki, E., Backman, J., Kesti, J., Hirsikko, A., Engelmann, R., O'Connor, E., Leskinen, J. T. T., Shang, X., Korhonen, H., Lihavainen, H., Romakkaniemi, S., and Komppula, M. (2020), *Optical and geometrical aerosol particle properties over the United Arab Emirates*, Atmos. Chem. Phys., 20, 8909–8922, https://doi.org/10.5194/acp-20-8909-2020.

Golnaz Roudsari, Bernhard Reischl, Olli H. Pakarinen, and Hanna Vehkamäki (2020) *Atomistic simulation of ice nucleation on silver iodide (0001) surfaces with defects,* J. Phys. Chem. C 124(1), 436-445. https://doi.org/10.1021/acs.jpcc.9b08502

Submitted

Juha Tonttila, Ali Afzalifar, Harri Kokkola, Tomi Raatikainen, Hannele Korhonen, and Sami Romakkaniemi: *Precipitation enhancement in stratocumulus clouds through airbourne seeding: sensitivity analysis by UCLALES*, submitted to Atmos. Chem. Phys. Discuss.

A tentative publication plan is provided at the end of this document in Appendix 2.

Presentations

New this reporting period

Tonttila, J., Afzalifar, A., Kokkola, H., Romakkaniemi, S. (2020): Modelling the Precipitation Enhancement by Hygroscopic Cloud Seeding in Warm and Mixed-Phase Clouds Using UCLALES-SALSA. *22nd Conference on Planned and Inadvertent Weather Modification,* Boston, Massachusetts, Amer. Meteor. Soc., https://ams.confex.com/ams/2020Annual/meetingapp.cgi/Paper/370639

Tonttila, J., Kokkola, H., Raatikainen, T., Ahola, J., Korhonen, H., Romakkaniemi, S. (2020): Model investigation into rain enhancement by hygroscopic seeding in mixed-phase convective clouds,

EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-12065, https://doi.org/10.5194/egusphere-egu2020-12065

Pakarinen, O., Roudsari, G., Reischl, B., and Vehkamäki, H. (2020): Effect of water confinement on heterogeneous ice nucleation, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-19008, https://doi.org/10.5194/egusphere-egu2020-19008

Reischl, B., Roudsari, G., Turtola, S., Pakarinen, O., and Vehkamäki, H. (2020): Towards understanding heterogeneous ice nucleation on realistic silver iodide surfaces from atomistic simulation, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-7758, https://doi.org/10.5194/egusphere-egu2020-7758

Cumulative prior to reporting period

Prior to this reporting period, a total of 19 presentations (oral/poster) had been given at national and international workshops and conferences.

APPENDIX 1: KEY SCIENTIFIC FINDINGS

WP1: Observation-based quantification of aerosol-cloud-precipitation interactions (lead Prof. Heikki Lihavainen)

A one-year measurement campaign was conducted to characterize background aerosol properties in the UAE region. The measurements contained measured quantities at the ground level (in-situ) and profile quantities (remote sensing).

Task 1.1: Aerosol, CCN and IN characterization

Aerosols were characterized on the ground level from a chemical and physical point of view. Aerosol properties had a clear diurnal cycle due to mixing in the boundary layer and wind direction change which was observed almost daily. Sulphate dominated aerosol composition in the region. Formation of new particles was observed almost daily, this was most likely to be related to the SO2 and consequent formation of sulphuric acid. The contribution of new particle formation events to cloud condensation nuclei (CCN) concentrations is under analysis. SO2 and black carbon concentrations had a clear diurnal cycle, but they were opposite. During night-time, the BC concentrations were clearly higher than during day-time, whereas SO2 were lower during night time compared to day time concentrations. CCN number concentration had the highest values in early summer. The CCN concentration had also a very strong diurnal cycle, the highest activation fractions were in the beginning and end of the day.

Frequent elevated aerosol layers above the boundary layer up to 11 km were observed. In total, 1130 aerosol particle layers were detected during the 1-year measurement campaign. Multiple aerosol layers were present in the majority of identified cases. For 58% of the cases the geometrical depth ranged between 0.4 and 0.8 km, thickest layers being over 2 km deep. On average slightly over 50 % of the aerosol load was observed to be in the free troposphere.

Clouds observed above the boundary layer were analysed. The results show that clouds are more frequent in spring and winter. An increase in cloud altitude and thickness was observed from October to December.

Task 1.2 Boundary layer dynamics characterization

The boundary layer structure had a very consistent diurnal cycle. The observed boundary height was between 1 and 1.5 km during the year. Strong surface winds commonly occurred, typically in the early afternoon. These winds caused rapid increase in aerosol concentration throughout the entire boundary layer. Strong winds from different directions in the upper level compared to the ground level were often observed, which indicates that upper level aerosol transport is not similar to transport at the ground level. Low level jets were also often present. Winds come from east during night and from west during day, which therefore brings aerosols to the site from different source regions depending on the time of the day.

Task 1.3 Evaporation of precipitation

Water vapour profiles were measured during dark hours. The boundary layer was reasonably moist, although it rarely reached saturation at the top, hence the lack of boundary layer clouds. Above the boundary layer, very dry layers were often observed in between the boundary layer and the next potentially cloudy layer. These dry layers, diagnosed as those layers with relative humidity less than 6 %, were very frequent, particularly during November to March, and were 1-2 km deep on average. Rain generated in clouds above such dry layers would then experience severe evaporation while falling through the deep dry layer, enough to prevent the rain from reaching the ground. This was observed to happen on a few occasions during the campaign, where rain was generated above an altitude of about 4 km but evaporated before reaching the surface after falling through a dry layer.

Task 1.4 Spatial extension

A clustered analysis was conducted to the air masses arriving at the site. Three out of five of the clusters were related to westerly air masses whereas one quite regional southerly air masses. The last was related to northerly and north-west air masses. The air mass trajectories also had a clear diurnal cycle.

WP2: Model simulations of optimal cloud seeding strategies (lead: Dr Sami Niemelä, Prof. Sami Romakkaniemi, Prof. Hanna Vehkamäki)

Task 2.1: Mesoscale meteorological modelling

In order to identify the meteorological conditions leading to rain formation in the UAE region, cloud seeding information of National Center of Meteorology (NCM) and satellite information of MODIS were used for finding all potential precipitation cases for the years 2014-2017. Thirty cases were found and were simulated with the mesoscale model HARMONIE-AROME, and two representative cases (a moderate forced convection case near mountain in summer, and a stratiform frontal cloud field in winter) were passed on to Task 2.2 for clouds scale simulation. The simulations by HARMONIE-AROME were validated by comparing the presence, location, and movements of clouds to satellite data from the MFG geostationary satellite Meteosat-7 of EUMETSAT. Furthermore, two additional test cases (September 19, 2017 and July 14, 2015) were compared with simulations conducted in another UAEREP funded project OCAL, which uses the WRF-NOAHMP model system, with respect to the vertical structure of clouds, as well as atmospheric fields within the entire target area.

The results show that a state-of-the-art meso scale weather prediction model can yield realistic simulations of winter-time stratiform precipitation systems as well as for summer-time forced convection. Operational forecasting of the potential for cloud seeding is therefore feasible from a modelling point of view.

Task 2.2: Cloud-scale modelling

The high-resolution cloud resolving model platform UCLALES-SALSA was used to investigate the seedability of summertime convective clouds in conditions typically occurring in the UAE. The model was chosen primarily because of the state-of-the-art description of aerosol-cloud microphysics built in the SALSA module. Even though our primary focus was on microphysical processes and the role of aerosol, it is important to consider the interaction with the cloud scale dynamic, whose representation is enabled by the high-resolution core of UCLALES-SALSA.

We first evaluated the model's performance in a simple marine stratocumulus cloud seeding setting, which also provided a rare instance of a field experiment with direct in-situ measurements of hygroscopic cloud seeding effects. The results from this investigation were very promising, with the model reproducing the observed seeding effects on the droplet size distribution. Next, we undertook a series of UCLALES-SALSA experiments focusing on summertime convective clouds over the UAE. These model experiments were based on NWP-data obtained from Task 2.1 and on the field observations conducted in WP1.

These experiments revealed the importance of mixed-phase microphysics in determining the hygroscopic seeding effects on rainfall. While the role of ice had been suggested before in some publications, the majority of literature to date on hygroscopic seeding has focused primarily on warm phase microphysics. In contrast, our results show that the cold precipitation process, especially riming, is highly important when hygroscopic seeding is performed in convective clouds. Our data shows that the seedability of a cloud can to an extent be determined by examining the rime fraction of the cloud particle population. However, further sensitivity tests indicate, that the relationship between rime fraction and cloud seedability is not fully ambiguous and, therefore, no single parameter alone is likely to provide a robust indicator.

Task 2.3: Molecular scale modelling

Molecular-scale simulations were undertaken to improve understanding of what characteristics make aerosol particles most efficient ice nuclei. Our model runs confirm recent experimental work on Si(100) surfaces that has highlighted the importance of small surface features such as surface defects, which function as active sites for ice nucleation. However, for commonly applied ice seeding nucleus silver iodide (AgI), we find that most microscopic defects (such as step edges, terraces, and pits) reduce both the ice nucleation and ice growth rates by up to an order of magnitude. Despite this, we managed to enhance the ice nucleation also compared to the very active flat AgI surface when we assumed wedge shaped structures with β-AgI (0001) surface as one of the two sidewalls, and slit systems by positioning two β-AgI (0001) slabs to mirror each other.

WP3: Statistical analysis (leads: Prof. Hannele Korhonen and Prof. Miikka Dal Maso)

The main aim here was to assess to what extent the rain enhancement potential of mature clouds could be predicted using machine learning if atmospheric conditions and aerosol properties were known at the cloud initial stage. Convolutional neural network (cnn) was found to capture the cloud-to-cloud variation of the average rime fraction from cloud-scale simulations conducted in Task 2.2. Furthermore, the vertical profile of rime fraction was also captured reasonably well on average, although for some individual clouds the results are poorer.

Before applying the developed methodology to ambient atmospheric cases, further research is needed. Critical open questions include what are the most important features in the input data that explain the good performance of cnn when modeling the overall vertical profile of rime fraction, and whether these results generalize to other models or different atmospheric conditions.