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برنامج الإمارات لبحوث علوم الاستمطار
UAE Research Program for Rain Enhancement Science

[ADVANCED STUDY ON PRECIPITATION ENHANCEMENT IN ARID AND SEMI-ARID REGIONS]

Final Report

UAE Research Program for Rain Enhancement Science

Reporting Period	
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EXECUTIVE SUMMARY

- **Summary of Scientific and Technical Progress vs. Plan:**【Data Analysis】 As scheduled in the plan for extended period, we performed a collocated analysis of CloudSat and geostationary satellite observations in an attempt to observationally probe the microphysical processes responsible for the warm rain formation for the purpose of identifying 'seedable clouds' suitable for the rain enhancement and their controlling microphysical processes. 【Laboratory Experiment】 As scheduled in the plan, to clarify the size dependency of hygroscopicity and chemical compositions of 3 types of flare particles, we have performed analysis of CCN counter measurement data using monodisperse particles, which were size-selected by DMA, and analysis of the EDS data of electron microscopy classified by particle sizes. 【Observation】 As scheduled in the plan, a further quality control of our aircraft data has been done, and the raw data and text data, including quick-look charts, were archived and uploaded on our web site. Through in-depth analysis of microphysical properties of natural clouds, we are preparing for its publication. 【Numerical Modeling】 As scheduled in the plan, using models, we continued the investigations on the effects of atmospheric aerosols and seeding aerosols on clouds and precipitation over the UAE. The new hygroscopic seeding scheme for double-moment cloud microphysics model was built on the CCN activation scheme newly introduced into CReSS to simulate hygroscopic seeding from below cloud base in a realistic way. Aerosol-cloud-precipitation integrated microphysics model has been developed and is being tested to run with initial and boundary conditions of various types of aerosols from the global aerosol model, SPRINTARS. 【Overall Objectives】 Most of primary objectives of this project had been almost completed as scheduled in the original plan. As scheduled in the plan for extended period, we have been conducting additional researches to achieve the objectives that had remained uncompleted at the end of third year. A few objectives that still remain uncompleted at this point of time will be completed in the next few months.

SCIENTIFIC AND TECHNICAL PROCESS

Overall Project:

- A collocated analysis of CloudSat and Meteosat satellite measurements suggests that the time-evolving information of cloud properties and their relations to the vertical structure can characterize different behaviors of the growth and decay processes. The results showed that the decaying and stop-growing cases occurring around CER=12.5 to 20μm have higher radar reflectivity in lower part of the cloud layer, compared to growing cases at the same CER range. Such a distinction of the cloud growth process at different cloud lifetime stages would enable more process-based detection of 'seedable clouds'.

  The additional experiments using the more accurate method revised the hygroscopicity of hygroscopic flare particles to be about 0.3. According to EDS analysis, hygroscopic flare and hybrid flare particles were mainly composed of KCl and CaCl2 and included more Ca and Mg components in the larger size mode than in the smaller size mode. Further investigations on CCN ability of salt MP without anti-caking agents, INP ability of MP with anti-caking agents (CaCO3, SiO2, Ca3(PO4)2) and MgO and INP ability of flare particles, especially in temperature range > -10 C, will be performed using the cloud simulation chamber in the next few months.

  The relationship between updraft velocities and thermodynamic parameters below the cloud base did not show any significant correlation, suggesting other parameters should be considered as the convection trigger to overcome the capping inversion. Inside updraft core, cloud droplets had a tendency to be larger in number concentration and water content and ice particles had a tendency to be larger in size and smaller in number concentration, compared to in other categories in each cloud layer. Cloud droplet concentrations near cloud base were typically on the order of 10^2 cm^{-3}_stp and BG aerosols larger than about 0.1 μm are thought to be activated into cloud droplets at water supersaturations between 0.1% and 0.5%.

  All three models (MRI-NHM, CReSS and NICAM), which had been optimized (tuned) their land surface parameters to properly reproduce clouds and precipitation over the UAE desert and Oman Mountains, have been used to investigate the effects of atmospheric aerosols and seeding aerosols on clouds and precipitation. High-resolution and realistic hygroscopic seeding experiments, CCN/IN sensitivity experiments, and clouds/precipitation experiments coupled with global aerosol model have been conducted. In order to evaluate the uncertainty limit of seeding effects simulated by numerical models, an inter-model comparison of the CCN and IN sensitivity experiments have been conducted. Investigations on an optimal seeding method, a new statistical evaluation method of seeding effect, and seasonal seeding effect will be continued using the numerical model with a new hygroscopic seeding scheme in the next few months. Aerosol-cloud-precipitation integrated model has been developed and is being tested to run with initial and boundary conditions of various types of aerosols from the global aerosol model, SPRINTARS. The model will provide us with much more realistic simulation results also in the next few months.

- CCN/IN sensitivity experiments, which were conducted to investigate possible maximum effects of hygroscopic seeding and glaciogenic seeding on precipitation from mixed-phase convective clouds, showed that hygroscopic seeding have the opposite effect of conventional hygroscopic seeding concept. That is, hygroscopic seeding to increase cloud droplet number concentration and decrease mean droplet size may enhance surface precipitation.

Individual Tasks/Projects:

Data Analysis:

Satellite-based analysis

We performed a collocated analysis of CloudSat and geostationary satellite observations in an attempt to observationally probe the microphysical processes responsible for the warm rain formation for the purpose of identifying 'seedable clouds' suitable for the rain enhancement and their controlling microphysical processes. The vertical microphysical structure obtained from CloudSat is put into the context of the time-evolving measurement of the high-frequency geostationary satellites. We analyzed the CloudSat and Meteosat merged data to investigate how the microphysical characteristics described by cloud optical depth (COD) and cloud effective radius (CER) tend to vary with time before and after the occurrence of different precipitation categories (i.e. non-precipitating, drizzle, and precipitating). We applied the same methodology to the Himawari and CloudSat merged data for comparisons to the Meteosat analysis. The analysis showed that both COD and CER tend to increase (decrease) with time in precipitating clouds compared to those before (after) the CloudSat overpass time. The vertical microphysical structure and its transition were also analyzed in the form of the statistics that are separately composited for growth and decay stages defined according to temporal changes of CER. The results showed that the decaying and stop-growing cases occurring around CER=12.5 to 20μm have higher radar reflectivity in lower part of the cloud layer, compared to growing cases at the same CER range. This suggests that cloud vertical structures are different between growing and decaying stages of cloud lifecycle. Such a distinction of the cloud life stages enables more process-based detection of 'seedable clouds'.

Laboratory Experiments:

In order to clarify the effectiveness of seeding agents, physico-chemical properties, such as size distribution, cloud condensation nuclei (CCN) and ice nucleating particles (INP) abilities of three types of flare particles (hygroscopic flare, AgI flare and hybrid flare) have been investigated by using CCN counter, IN counter and several aerosol instruments. The hybrid flare and the hygroscopic flare particles typically had a bi-modal size distribution with a smaller mode diameter of around 140-170 nm and a larger mode diameter of around 1 μm, while AgI flare particles has a mono-modal size distribution with a mode diameter of 90-100 nm.

To clarify the size dependency of hygroscopicity and chemical composition ratio of 3 types of flare particles, we have performed analysis of CCN counter measurement data using monodisperse particles, which were size-selected by DMA, and analysis of the EDS data of electron microscopy classified by particle sizes. The additional experiments using the more accurate method revised the hygroscopicity of hygroscopic flare particles to be about 0.3. According to EDS analysis, hygroscopic flare and hybrid flare particles were mainly composed of KCl and CaCl2 and included more Ca and Mg components in the larger size mode than in the smaller size mode. AgI flare particles didn't include CaCl2.

Since the measurable supersaturation range of CCNC is from 0.1% to 2.0 %, it is impossible to directly obtain the hygroscopicity of particles having hygroscopicities of 0.1 or greater and diameters of 0.3 μm or larger using the accurate method with monodisperse particles. In order to assess the feasibility of hygroscopicity measurement for larger hygroscopic flare particles, we developed a new method to estimate the hygroscopicity from size distributions of dry aerosol particles and of droplets grown in CCNC.

Further investigations on CCN ability of salt MP without anti-caking agents, INP ability of MP with anti-caking agents (CaCO3, SiO2, Ca3(PO4)2) and MgO and INP ability of flare particles, especially in temperature range > -10C, will be performed using the cloud simulation chamber in the next few months.

Observations:

Aircraft observation

We had conducted 14 research flights from Sep. 5 to Sep. 24 in 2017 over the UAE region. Thirteen of the B200T flights were coordinated with the C-90 flights. In addition to the seeding experiment, several flights provided us in-situ measurements of natural clouds. Typically, the cloud base height was around 4 km and the freezing level was around 4.5 km during the IOP. We analyzed histograms of vertical velocity near cloud base height in each case, which ranged mostly within plus and minus 4 m/s. Here two cases (Sep. 16 as Case-I and Sep. 20 as Case-II) of summertime diurnal convective clouds were compared in terms of virtual potential temperature, water vapor mixing ratio, and number concentrations of back-ground (BG) aerosols. There existed a capping inversion layer at the top of convective mixed layers (~4.8 km in height).

In order to investigate the trigger of convection in natural clouds, the potential temperature and water vapor density outside clouds near cloud base height were plotted as a function of vertical velocity. There found no significant trends, and other factors except for potential temperature anomaly should be considered as the convection trigger to overcome the capping inversion.

Vertical profiles of cloud droplets showed that the median volume diameter and liquid water content (LWC) gradually increased as the height increases from cloud base to cloud top. The both properties in Case-I were larger than those in Case-II, although the number concentrations were comparable in both cases. The regions in updraft core exhibit the highest values, with its neighbors and other regions similar in values. Near cloud top layers, ice particles had a tendency of smaller number concentrations in category of updraft core regions, and larger in other categories. Inside updraft core, the ice particles had a tendency to be larger in size and smaller in number concentration, compared to in other categories in each cloud layer.

Three types of seeding had been conducted, using CaCl2 hygroscopic (HYG) flare, silver iodide (AgI) flare, or both flares simultaneously during the IOP in 2017. In general, the flare particles of around 0.1 µm in size are dominant in both types. The whole size distributions can be fitted with two lognormal distributions. The mode size of HYG flare particles are larger than that of the AgI ones, which is consistent with the results from laboratory experiments at MRI.

The measured cloud droplet concentrations near cloud base were typically on the order of 10^2 cm^{-3}_stp. When comparing the number concentrations of aerosols, cloud droplets, and CCN near cloud base, BG aerosols larger than about 0.1 µm are assumed to be activated into cloud droplets at water supersaturations between 0.1% and 0.5%.

Through in-depth analysis of microphysical properties of natural clouds, we are preparing for its publication.

Numerical Modelling:

MRI-NHM

Numerical simulations have been performed by using a numerical weather prediction model (MRI-NHM) with horizontal resolutions of 1 km and 200 m to reproduce the observed clouds for evaluating model performances. In the simulations, the amplitude of diurnal variation of air temperature from the surface to 5 or 6 km height is smaller than the observation in the middle troposphere, while, in the layers lower than 2 km height, the simulations well reproduces the amplitude. Relative humidity is overestimated in the lower layers in the simulations. The observed relative humidity profile shows the maximum from 3- to 6-km height at all times. The observed dry and water vapor saturated layers below and above the 4.5 km height, respectively, are well represented by the simulations. In the water vapor saturated layers, cloud water is observed on the order of 1 g kg^{-1} at most in mixing ratio. The model well represents this feature. We plan to examine number concentration of cloud droplets and other microphysical features in the simulations by comparing with the observation, and to adjust some microphysical parameters in the model for improving the model performance.

Using simulation results of MRI-NHM with 1 km horizontal resolution, physical predictors of surface precipitation have been investigated for diurnal convective clouds over the 500 km x 400 km area centered at Al Ain in September 2017. Simple correlation analysis and multiple regression analysis are ongoing to understand the relation between surface precipitation and each physical predictor.

<u>CReSS</u>

We had been performed sensitivity experiments of precipitation to the increase/decrease of cloud condensation nuclei (CCN) or more directly cloud droplet number concentrations to assess a possible maximum seeding effect. For numerical models that express cloud water and rainwater as single-moment variables, including the original version of CReSS, hygroscopic seeding effect was simulated by changing the prescribed number concentration of cloud water.

In order to simulate hygroscopic seeding from below cloud base in more realistic, but rather simple way, we introduced a new hygroscopic seeding scheme into CReSS with a new cloud microphysics scheme which expresses all the hydrometeors as double-moment variables. And we investigated its performance through idealized simulations of hygroscopic seeding of mixed-phase convective clouds over the UAE and its surroundings.

The new hygroscopic seeding scheme was built on the CCN activation scheme newly introduced into CReSS. The coefficients, C and k, of the CCN activation spectrum proposed by Twomey (1959) can be changed at grid points where a given atmospheric condition meets so as to simulate more realistic and efficient hygroscopic seeding. This facilitates an investigation of optimal seeding conditions. The coefficients of background CCN spectra at initial time are given as a vertical profile, which also enable us to study aerosol effects on microphysical structures of multi-layer clouds associated with synoptic scale disturbances.

Through idealized simulations of summertime mixed-phase convective clouds, we investigated hygroscopic seeding effects on surface rainfall by changing the value of C from background value of 300 cm^{-3} to 30 cm^{-3} (LSEED case) or 3000 cm^{-3} (HSEED case) at grid points with updraft velocity velocities > 0.3 $m\ s^{-1}$ just below cloud base.

HSEED case showed a significant increase in surface precipitation, but also showed a significant dependence of seeding effects on cloud characteristics (mainly cloud top height) and cloud microphysics schemes. In parallel to hygroscopic seeding simulations, we are validating/improving cloud microphysics schemes against aircraft observation data collected over the UAE in the summer of 2017.

Seeding effects on summertime mixed-phase convective clouds over the UAE will be investigated through the simulations using the improved numerical model under more realistic and appropriate seeding conditions in the next few months.

Aerosol (atmospheric aerosol and seeding aerosol)-Cloud-Precipitation Integrated Microphysics Scheme has been developed and is being tested to run with initial and boundary conditions of various types of aerosols from the global aerosol model, SPRINTARS. The model will provide us with much more realistic simulation results also in the next few months.

<u>NICAM</u>

We conducted numerical simulations with the NICAM model over the UAE region for aerosol transport processes with NICAM-SPRINTARS, the aerosol-coupled version of the NICAM model, and sensitivity experiments employing two different nucleation schemes to compare aerosol impacts on cloud condensation nuclei over the UAE region. The simulations are performed over the 3 days from 15th to 18th, September 2015, during which convective rainfall events occurred. In this project year, we have focused on comparisons of the NICAM-SPRINTARS simulations with satellite measurements of aerosols over the UAE region to expose that the model tends to underestimate the aerosol loadings, dominated by soil dust particles, over the UAE region. The sensitivity experiments with two nucleation schemes are also compared to show that the CCN number concentrations are generally underestimated due to the underestimates of AOD to somewhat different extents depending on nucleation schemes. The first attempt of this kind to investigate the aerosol-cloud interaction over the UAE region highlights a need for continued effort with multiple models and various observations in future studies. As a step toward such a community approach with inter-comparisons of multiple models, we collaborated with other funded team of the UAEREP program to pursue inter-comparisons of the two models used in the program, i.e. NICAM and WRF, regarding their performances over the UAE region in an attempt to identify model uncertainties in representing surface precipitation and relevant meteorological fields over the arid region.

CLOSING SECTION

Summary:

Data Analysis:

Solar radiation and rainfall data of UAE/NCM AWS's data and Meteosat-8 data showed the seasonal, geographical and diurnal variations in the occurrence frequency of clouds possibly suitable for rain enhancement in the UAE and its surrounding areas. The analysis results were confirmed by the year-round ground-based remote sensing data at Al Ain Airport. Meteosat-8 data analysis showed that seedable clouds (liquid-dominant clouds with LWP > 0.3 mm) occur at frequency of 4 - 7 % of time over the northern part of the UAE during winter months and at 1 - 5 % of time over the mountainous areas during summer months. Transition months such as April and May show less percentage of seedable clouds relative to the winter and summer months. Optically-thick clouds (roughly equivalent to clouds with LWP > 0.3 mm) derived from UAE/NCM AWS's surface solar radiation measurements showed a spatial distribution of their occurrence frequency consistent to those of Meteosat-8-derived daytime seedable clouds.
A collocated analysis of CloudSat and geostationary satellite observations was performed in an attempt to observationally probe the microphysical processes responsible for the warm rain formation for the purpose of identifying 'seedable clouds' suitable for the rain enhancement and their controlling microphysical processes. The result suggests that cloud vertical structures are different between growing and decaying stages of cloud lifecycle and may enable more process-based detection of 'seedable clouds'.

Laboratory Experiments:

In order to clarify the effectiveness of seeding agents, physico-chemical properties, such as size distribution, cloud condensation nuclei (CCN) and ice nucleating particles (INP) abilities of three types of flare particles (hygroscopic flare, AgI flare and hybrid flare) were investigated by using cloud simulation chamber, CCN counter, IN counter and several aerosol instruments. Particle morphology and internal mixing state of elemental components were also investigated from electron microscopic analysis. We focused on hygroscopic parameter κ and temperature-deterministic ice nucleation active surface site (INAS) density for each particle size mode. The hybrid flare and the hygroscopic flare particles typically had a bi-modal size distribution with a smaller mode diameter of around 140-170 nm and a larger mode diameter of around 1 μm, while AgI flare particles has a mono-modal size distribution with a mode diameter of 90-100 nm.
Particles smaller than 0.1 μm and produced from hygroscopic flare, AgI flare and hybrid flare have κ-values of 0.2 - 0.3, 0.4 - 0.5, and 0.6 – 0.7, respectively. The κ-values of hygroscopic flare particles was evaluated to be around 0.6 using newly developed method.
The number of INP induced per gram of AgI for AgI flare and hybrid flare were about 10^{14} and 10^{12}-10^{13} particles at temperatures of -15 °C. Almost all AgI particles activate at temperatures down to -15 °C and AgI particles produced from AgI flare and hybrid flare could act as not only immersion freezing nuclei, but also deposition nuclei so that the "AgI" particles started to activate below water saturation. Hybrid flare particles had INAS density of 10^{11} - 10^{12} m^{-2} at temperatures of -15 °C, while AgI flare particles had INAS density of 10^{13} m^{-2}.
According to EDS analysis of electron microscopy, hygroscopic flare and hybrid flare particles were mainly composed of KCl and CaCl2 and included more Ca and Mg components in the larger size mode than in the smaller size mode. AgI flare particles didn't include CaCl2.

Observations:

Aircraft observation

Our field campaign of aircraft observations had successfully been conducted over the UAE regions as well as along ferry flight tracks between UAE and Japan. We had conducted 14 research flights from Sep. 5 to Sep. 24 in 2017 over the UAE region under guidance of trial forecast by our three models. Thirteen of the B200T flights were coordinated with the C-90 flights. In addition to the seeding experiment, several flights provided us in-situ measurements of natural diurnal convective clouds.

a. Seeding experiments

Three types of seeding had been conducted, using CaCl2 hygroscopic (HYG) flare, silver iodide (AgI) flare, or both flares simultaneously during the IOP in 2017. In general, the flare particles of around 0.1 µm in size are dominant in both types. The whole size distributions can be fitted with two lognormal distributions. The mode size of HYG flare particles are larger than that of the AgI ones, which is consistent with the results from laboratory experiments at MRI. Although the number of seeding experiments and analyzed cloud droplet size distributions in updraft cores in seeded and unseeded regions were limited, it was difficult to find clear seeding signatures in terms of broadening of cloud droplet size distributions beyond 30 µm, increase in mean droplet size nor decrease in total cloud droplet number concentrations, probably due to much smaller amounts of seeded materials.

b. Microphysical structure and precipitation mechanisms in natural clouds

Most of diurnal convective clouds we observed were developed from stratocumuli confined in below the top of deep convective boundary layer in midafternoon. Typical diurnal convective clouds were characterized by cloud base height of 4 km, freezing level of 4.5 km, cloud top temperatures near or slightly warmer than -10 C and strong temperature inversion just above cloud bases. The aerosols that act as CCN are activated at water supersaturations of 0.2 to 0.5% in updraft cores near cloud bases, and number concentrations of activated cloud droplets near cloud base were several hundred cm^{-3} and decreased with altitude due to collision-coalescence of cloud droplets and entrainment of surrounding dry air, except near cloud tops. Usually the clouds had ice crystals and graupels and such ice particles showed a characteristic spatial distribution with their larger particle sizes and smaller number concentrations in the updraft cores compared to the surrounding area.

c. Background aerosols

In order to conduct effective and efficient cloud seeding experiments, it is essential to know CCN and INP capabilities of BG aerosols in the atmosphere and their spatial and temporal distributions. BG aerosols in desert areas were mostly composed of mineral dust in coarse mode and of ammonium sulfate with soot inclusion in fine mode. The BG aerosols in a coastal area were generally composed of the same as that in the desert, although small number of sea-salt particles existed in coarse mode. The vertical profiles of aerosol number concentrations (corrected for STP conditions) showed rather constant below cloud base height. INP concentrations typically ranged on the order of a few to a few tens L^{-1} and there was no significant height dependency. CCN concentrations were typically 1,000 – 3,000 cm^{-3}_stp at SSw of 0.5% and generally depended on the space and time.

Year-round ground-based observation

We conducted the year-round ground-based observation at Al Ain from January 2017 to January 2018 using a Multi-frequency microwave radiometer (MP-3000), a Parsivel optical disdrometer, and a K-band Doppler radar (Micro-Rain Radar; MRR). Combined with cloud top temperature derived from Meteosat-8, the data from the three instruments provided us the occurrence frequency of possibly seedable clouds over Al Ain; small values (~ 1% in time) of the occurrence frequency in cold seasons and very small values in warm seasons. Meteosat-8 – induced cloud microphysics property data was validated against the ground-based remote sensing data.

Numerical Modelling:

Since, with the original configuration, all three models (MRI-NHM, CReSS and NICAM) failed to reproduce the diurnal variation of land surface temperature and surface air temperature, which gave adverse effect on the reproducibility of clouds and precipitation. The three models were optimized (tuned) their land surface parameters to properly reproduce clouds and precipitation over the UAE desert and Oman Mountains. It is demonstrated that the optimized land surface parameters significantly improve the reproducibility of seasonal variations of cloud coverage and precipitation patterns in the UAE and its surrounding areas and characteristics of summertime diurnal convective clouds and their spatio-temporal evolutions.

High resolution (up to 200 m horizontal grid spacing) numerical simulations using MRI-NHM with the bulk microphysics parameterization, which implemented new hygroscopic seeding scheme based on the lookup table, have been conducted for the 11 September 2015 case. The simulation results showed slight decrease in cloud droplet number concentrations, but did not show any significant increase in surface precipitation, probably due to much smaller amount of seeding materials.

Numerical simulations of aerosol transport processes over the UAE region were performed from 15th to 18th, September 2015, using NICAM-SPRINTARS, the aerosol-coupled version of the NICAM model. Comparisons of the NICAM-SPRINTARS simulations with satellite measurements of aerosols over the UAE region exposed that the model tends to underestimate the aerosol loadings, dominated by soil dust particles. The sensitivity experiments with two nucleation schemes are also compared to show that the CCN number concentrations are generally underestimated due to the underestimates of AOD to somewhat different extents depending on nucleation schemes. The first attempt of this kind to investigate the aerosol-cloud interaction over the UAE region highlights a need for continued effort with multiple models and various observations in future studies.

To investigate possible maximum seeding effects by hygroscopic and glaciogenic seeding, sensitivity of total precipitation to CCN and INP concentrations was investigated by using CReSS model. For CCN sensitivity tests, the prescribed cloud droplet number concentration is set 500 cm-3 for CNTL case, 100 for Low CCN case, 1000 for High CCN case, and 2500 for extremely high CCN case. For INP sensitivity tests, we used default heterogeneous ice nucleation formula for CNTL case, one tenths of the default values for Low INP case, ten times the default values for High INP case.

The condensation/deposition amounts for HCCN and ECCN cases show almost 30 - 50 % increase compared with CNTL case due to dynamic seeding effect: High droplet number concentrations reduce mean droplet size, weaken warm rain processes and consequently more cloud water is carried up beyond freezing level. Freezing of more cloud water increases latent heat release and strengthens convection, leading to an increase of total condensation amount. The condensation/deposition amounts for HIN case show almost 10 - 20 % increase over foothill and mountain areas compared with CNTL case due to static seeding effect: High INP concentrations increase solid hydrometer number concentrations and enhance their deposition growth, resulting in an increase of total deposition amount.

Over foothill area, HCCN, ECCN and HIN cases showed large seeding effects on total precipitation amount at cloud base height, reflecting the enhanced domain-averaged condensation/deposition amount for these cases. Over mountain area, the reason for the diminished or even negative seeding effect of HCCN, ECCN and HIN cases is a kind of over-seeding, i.e., too many ice particles from homogeneous freezing of cloud droplets and additional heterogeneous freezing suppress the growth of ice particles into large precipitation particles. Over desert area, cloud top height is lowest among the three areas, and the layer where cold rain processes are dominant becomes shallower. The reasons for the negative seeding effects of HCCN/ECNN and HIN cases are less efficient warm rain processes due to reduced mean cloud droplet size and less efficient accretion growth due to reduced mean precipitating particle size, respectively. Note that air with very low R.H. and high temperatures in the convective boundary layer evaporates 2/3 of precipitation amount at cloud base height before reaching the surface and obscures the seeding effect on total precipitation amount at the surface.

Hygroscopic seeding of mixed-phase convective clouds where homogeneous freezing does not operate may be effective if it increases cloud droplet number concentration and decrease mean droplet size, which means that hygroscopic seeding has the opposite effect of conventional hygroscopic seeding concept for warm clouds.

Progress against original plan

Data analysis
- Occurrence frequency of seedable clouds (done by M24)
- Validation of satellite algorithms (done by M27)
- Microphysical structures of aerosol, clouds and precipitation over the UAE derived from satellite data (done by M48)

Laboratory experiments
- Instrument upgrade (done by M12)
- Characterization of seeding materials (almost done by M42)
- Seeded/Unseeded experiments (almost done by M36, but being continued *1)

Observation
- Ground-based multi-wavelength remote sensor observation
  - Year-round monitoring (done by M24)
  - Data quality control (done by M27)
  - Archive (done by M27)
  - Analysis (done by M36)
- Aircraft observation
  - IOP (done by M18)
  - Data quality control (done by M42)
  - Archive (done by M42)
  - Analysis (done by M48)

Numerical modeling
- Development of seeding scheme
  - Hygroscopic seeding (lookup table) (done by M36)
  - Aerosol-cloud-precipitation integrated scheme (being continued*2)
- Validation/Improvement of numerical models (done by M24)
- Comparison with aircraft and ground-based observations (done by M42)
- Development of statistical evaluation method with help of physical predictors (being continued*3)
- Development of optimal seeding methods (being continued*4)
- Evaluation of seasonal seeding effects (not yet*5)

*1 Further investigations on CCN ability of salt MP without anti-caking agents, INP ability of MP with anti-caking agents ($CaCO_3$, SiO_2, $Ca_3(PO_4)_2$) and MgO and INP ability of flare particles, especially in temperature range > -10C, will be performed using the cloud simulation chamber in the next few months. The experiments are postponed due to COVIR-19 pandemic.
*2 The scheme has been developed and is being tested to run with initial and boundary conditions of various types of aerosols from the global aerosol model, SPRINTARS. CReSS implemented with the scheme will provide us with much more realistic simulation results also in the next few months.
*3 Using simulation results of MRI-NHM with 1 km horizontal resolution, physical predictors of surface precipitation have been investigated for diurnal convective clouds over the 500 km x 400 km area centered at Al Ain in September 2017. Simple correlation analysis and multiple regression analysis are ongoing to understand the relation between surface precipitation and each physical predictor.
*4 The new hygroscopic seeding scheme introduced into CReSS, where the coefficients, C and k, of the CCN activation spectrum proposed by Twomey (1959) can be changed below cloud base depending on cloud properties, will provide us with optimal seeding conditions in the next few months.
*5 Seasonal seeding effects on summertime mixed-phase convective clouds over the UAE will be investigated through the simulations by using the improved numerical model using more realistic and appropriate seeding conditions in the next few months.

Recommendation:

Research Topics:

In order to correctly understand the competing effect of seeded and ambient background aerosol particles and evaluate glaciogenic and hygroscopic seeding effects on precipitation, numerical models that are implemented with both seeded and background aerosols as prognostic variables should be developed based on laboratory experiments, validated against in-situ aircraft observations and used for the researches of rain enhancement by cloud seeding.

An effectiveness of rain enhancement in nourishing groundwater in the UAE should be investigated using a combination of atmospheric cloud model and hydrological model.

If it turns out that artificial rainfall on the western side of Oman Mountains can nourish groundwater in the UAE, the possibility of rain enhancement by cloud seeding on both eastern and western sides of Oman Mountain at the same time should be investigated more intensively.

In our project, we focused on rain enhancement for summertime diurnal convective clouds. However, cloud systems associated with synoptic-scale disturbances in winter months bring most of annual precipitation over the UAE and seem to include seedable clouds (clouds with LWP > 0.3 mm) more frequently. Therefore, it may be worth investigating the feasibility of rain enhancement for the cloud systems , especially in northern part of UAE although it is generally said that the clouds are not suitable for cloud seeding because high concentrations of ice particles formed near cloud top with low temperatures naturally sweep out most of cloud droplets.

Research Strategy:

For the last three cycles, UAEREP selected projects with variety of purposes, which may relate to rain enhancement science to some extent. But it seems difficult to unite the results from such projects to promote the rain enhancement science leading to feasibility study and development/improvement of rain enhancement technologies useful in arid and semi-arid regions. Next time, from the beginning, you had better organize a big research program composed of research projects with the same research vector (research projects aiming to concretely develop, evaluate, and verify the components of the artificial rainfall hypothesis that are likely to be realized).

PUBLICATIONS/PRESENTATIONS

Publications

- **New this Reporting Period**

  Flossmann, A. I., M. Manton, A. Abshaev, R. Bruintjes, M. Murakami, T. Prabhakaran, Z. Yao, 2019: Review of advances in precipitation enhancement research. Bull. Amer. Meteor. Soc., 100, 1465-1480.

  Niranjan Kumar, K., and K. Suzuki, 2019: Assessment of seasonal cloud properties in arid/semi-arid regions from geostationary satellite data, Remote Sens. Envi., 228, 90 -104.

  Kuo, T.-H., M. Murakami, T. Tajiri, and N. Orikasa, 2019: Cloud condensation nuclei and immersion freezing abilities of Al2O3 and Fe2O3 particles measured with an MRI cloud simulation chamber. J. Meteor. Soc. Japan, 97, 597−614..

  Hashimoto, A., N. Orikasa, T. Tajiri, Y. Zaizen, and M. Murakami, 2019: Numerical simulation of shallow cloud formation in the United Arab Emirates, CAS/JSC WGNE Research Activities in Atmospheric and Oceanic Modelling 49, 5-09

- **Cumulative Prior to this Reporting Period**

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Invention Disclosures/Filed Patents

- New this Reporting Period
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OTHER INFORMATION

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APPENDICES (IF ABSOLUTELY NECESSARY)