ABSTRACTS

SESSION 1: LEVERAGING SATELLITE OBSERVATIONS TO IMPROVE OPERATIONS

WEDNESDAY, APRIL 29 | 08:30 – 10:00 AM

Identification of Clouds Microphysical Seedability in an Actionable Manner

Dr. Daniel Rosenfeld[1]

[1]The Hebrew University of Jerusalem, Jerusalem, Israel
[2]Wuhan University, Wuhan, China
[3]Muhamad Ben Zayed University of Artificial Intelligence, Abu Dhabi, United Arab Emirates
[4]University of California San Diego, San Diego, CA, United States

Here we present an overview of the project, which is funded by the UAEREP 5th cycle. Satellite and radar measurements provide the only practical means to measure clouds over the large expanses where rain enhancement is sought. Only a fraction of these clouds is suitable for seeding. Therefore, identifying their seedability in an actionable way is of prime importance. Seedability is defined here as the amount of enhanced precipitation if the cloud was seeded optimally. Seedability varies greatly with background aerosol and meteorological conditions. Given this large variability, the seeding effort should be focused on the clouds with the greatest seedability, when they exist.

We develop a machine learning method for near real-time diagnosis of the seedability of cloud clusters in an actionable manner, based on operationally available meteorological and satellite data. The training of the machine learning procedure will be based on model simulations of actual cases and the validation of the model by previously available aircraft and radar data. The validated simulated clouds will undergo seeding for determining their seedability by various methods. This has to be done on simulated clouds because, in reality, we don't have sufficient observations of cloud properties that are coupled with satellite observations to allow machine learning training. To overcome this limitation, a cloud radiative transfer model that operates on the numerically simulated clouds produces simulated multispectral satellite and radar images. Each simulated image of a cloud cluster has its seedability. A machine learning procedure is trained based on the meteorological and satellite data for estimating seedability, accounting for potential differences between simulated and real images.

This presentation will show the sensitivity of clouds to different aerosols in several cases, and the manifestation in the simulated satellite imagery.

A companion presentation will show the application of the machine learning to the simulated satellites to obtain the cloud properties that determine their seedability.

Acknowledgements: This work was supported by the National Center of Meteorology, Abu Dhabi, UAE, under the UAE Research Program for Rain Enhancement Science (UAEREP).

Where are the Zigzags? An Investigation into the Relative Rarity of Aerial, Cool-Season Seeding Signatures as Seen by Geostationary Satellite

Mr. Caleb Steele[1]

[1]Weather Modification International, Fargo, ND, United States

Aerial application of seeding material at or near the top of cool-season orographic clouds is a common and efficient form of weather modification employed to enhance snowpack and augment water storage (Geerts and

Rauber 2022). Field campaigns like SNOWIE (Tessendorf et al 2019) verified the conceptual model and chain of events of glaciogenic cloud seeding, as well as the difficulty and caveats to observing such seeding signatures using radar (Zaremba et al 2023). With advances in geostationary satellite instruments like the GOES ABI, HIMAWARI-AHI, and MSG-SEVIRI, which deliver spectral bands at a high temporal and spatial resolution, cloud microphysics analysis for weather modification operations can be increasingly performed with this real-time dataset. However, while many examples of glaciating "zigzags" have been found, these represent a minority of operational cases, even when accounting for the limitations of satellite observations (such as time-of-day, line-of-sight/multiple cloud layers, etc.).

This work uses case studies of operational missions to test the hypothesis this apparent lack of efficacy is simply a limitation of the instrumentation – that these signatures are extremely dependent on cloud-top ice habit and the satellite's ability to "see" such a habit. Several positive and negative cases are examined with GOES-R series satellite data combined with High Resolution Rapid Refresh (HRRR) and in-situ Cloud Water Inertial Probe (CWIP) data utilizing the ice habit diagnoses following the revised diagrams in Hueholt et al (2022).

MTG-FCI Cloud Microphysics for Weather Modification: Effective Radius Retrieval, Warm-Rain Diagnostics, and Large-Viewing-Angle Correction

Mr. Shuxin Dai[1], Lin Zang[1], Daniel Rosenfeld[2]
[1]Wuhan University, Wuhan, China
[2]The Hebrew University of Jerusalem, Jerusalem, Israel

Weather-modification operations and post-event evaluation require continuous, physically consistent monitoring of cloud microstructure. We present an Metosat Third Generation Flexible Combined Imager (MTG-FCI) (0° full disk) workflow to retrieve cloud mask/phase, cloud-top temperature (CTT), and cloud particle effective radius (r_e) over the United Arab Emirates (UAE), and we further test the method on additional cases elsewhere. Cloud detection and phase discrimination are based on combined visible–near-IR reflectances (0.4–2.2 μm) with thermal-IR channels (10.8, 12.3, 13.4 μm). CTT is obtained from split-window brightness temperatures, providing the thermodynamic context for microphysical interpretation.

To retrieve r_e for both liquid and ice clouds, we first estimate the solar-reflective component at 3.8 μm via a multi-channel correction that leverages the 3.8 μm measurement, thermal-IR constraints (10.8/12.3/13.4 μm), and viewing/illumination geometry. We then invert r_e using a look-up-table (LUT) approach. The resulting r_e fields, combined with CTT, enable CTT–r_e (T–r_e) diagnostics for tracking cloud evolution at geostationary cadence and highlighting warm-rain-favorable regimes (e.g., warm cloud tops with enlarged droplet sizes).

A key limitation for geostationary shortwave applications is viewing-angle-dependent radiance brightening under large satellite zenith angles, which is strongest at shorter wavelengths (notably 0.4 μm) and is further amplified when solar zenith angles are large. We introduce a radiance-domain background-scattering correction parameterized by satellite zenith angle, wavelength dependence, and a low-view reference background radiance. Comparisons with collocated polar orbiting VIIRS scenes indicate improved cross-sensor consistency in large-viewing-angle regions, extending the usability of MTG shortwave reflectances and stabilizing derived RGB products. These advances strengthen MTG-based support for weather-modification targeting and objective assessment.

Acknowledgements: This work was supported by the National Center of Meteorology, Abu Dhabi, UAE, under the UAE Research Program for Rain Enhancement Science (UAEREP).

CloudSeedAI: Machine Learning-Based Identification of Cloud Seeding Susceptibility from Satellite Observations

SESSION 1: LEVERAGING SATELLITE OBSERVATIONS TO IMPROVE OPERATIONS

Ms. Georgia Nicolaou[1], Daniel Rosenfeld[2], Duncan Watson-Parris[1], Salman Khan[3], Feiyue Mao[4], Guy Dagan[2], Gedaliya Kitrossky[2], Weijie Kong[4], Shuxin Dai[4], Hanan Ghani[3], Barry Lynn[2], Guy Pulik[2]
[1]*University of California, San Diego, San Diego, CA, United States*
[2]*The Hebrew University of Jerusalem, Jerusalem, Israel*
[3]*Muhamad Ben Zayed University of Artificial Intelligence, Abu Dhabi, United Arab Emirates*
[4]*Wuhan University, Wuhan, China*

Rain enhancement over the Arabian Peninsula faces a fundamental challenge: only a fraction of clouds are suitable for seeding, and identifying those with the greatest precipitation potential in real time is critical for operational success. CloudSeedAI addresses this by developing a machine learning framework for near-real-time diagnosis of cloud seeding susceptibility from satellite data, trained on WRF spectral bin microphysics simulations under contrasting aerosol regimes paired with RTTOV-generated synthetic multispectral imagery.

We first demonstrate that cloud microphysical fields can be retrieved from synthetic satellite imagery via a U-Net inverse mapping, achieving R^2 > 0.90 across most variables, including cloud water, ice, rain, snow, graupel, and droplet number concentration, establishing the feasibility of satellite-driven microphysical inference.

Building on this, a FiLM-conditioned U-Net takes synthetic MSG imagery as input and jointly predicts cloud microphysical state conditioned on aerosol scenario. By training simultaneously across baseline and seeded WRF experiments, the model learns to predict how clouds respond to various seeding agents, like ice nucleating particles, hygroscopic flares, and salt micro-powder. Seedability, expressed as percentage precipitation enhancement relative to the unseeded baseline, is then diagnosed spatially for each method from the difference between conditioned predictions, restricted to cloudy regions identified via column-integrated water path.

By training on RTTOV-simulated imagery and adapting to real MSG observations, the framework targets operational deployment on MTG, translating satellite data into method-specific seedability guidance to focus seeding operations on the right clouds, with the right agent, at the right time.

Acknowledgements: This work was supported by the National Center of Meteorology, Abu Dhabi, UAE, under the UAE Research Program for Rain Enhancement Science (UAEREP).

DISCUSSION PANEL 1

ADVANCING CREDIBILITY: ASSESSING PROGRAM IMPACTS AND DEMONSTRATING VALUE IN WEATHER MODIFICATION

WEDNESDAY, APRIL 29 | 10:20 – 11:20 AM

SESSION 2: SCIENCE IN CONTEXT: COMMUNICATION, STANDARDS, AND DECISION-MAKING IN WEATHER MODIFICATION

WEDNESDAY, APRIL 29 | 11:20 – 12:00 PM

From Perception to Policy: Proactive Communication in Weather Modification

Ms. Kala Golden[1]

[1]*Weather Modification International, Fargo, ND, United States*

SESSION 2: SCIENCE IN CONTEXT: COMMUNICATION, STANDARDS, AND DECISION-MAKING IN WEATHER MODIFICATION

Weather modification is increasingly shaped by a policy environment influenced by misinformation, conflated narratives, and rapidly amplified public perception. As social media and digital platforms become primary sources of information, public understanding (and misunderstanding) can scale quickly, influencing not only opinion but also legislation, regulatory direction, and program funding. Recent efforts to restrict or ban operations in multiple regions reflect how easily misconceptions can translate into policy with real operational consequences.
At the same time, growing water scarcity and increasing weather extremes have brought heightened attention to weather modification. Interest in the field is expanding more rapidly than ever before, often outpacing public understanding of both the science and its limitations. Broader skepticism toward science and research further complicates this landscape, reinforcing the need for clear, credible, and consistent communication.
Gaps in both research and communication remain. Continued investment in research is essential to better understand outcomes, refine methodologies, and support informed decision-making. At the same time, the way science is communicated must evolve. Technical information is not always conveyed in ways that resonate with broader audiences, and inconsistencies in how capabilities and uncertainties are described can undermine credibility.

A more deliberate and proactive approach is needed. In an environment defined by active, real-time information exchange, communication must move beyond static reporting toward continuous engagement. Transparency should include accessible, timely, and audience-specific communication, while creating meaningful opportunities for public engagement and input. Strengthening coordination across researchers, industry, and public agencies—and grounding programs in science, validation, and independent evaluation— will be critical to building trust.
As policy, perception, and funding become increasingly interconnected, effective communication will serve as a core responsibility— central to the credibility, viability, and future of weather modification programs.

Weather Modification Association - ASCE/EWRI Atmospheric Water Management Standards Committee Update

Dr. Thomas P. DeFelice[1], Dr. Conrad Keyes Jr[1,2]

[1]*American Society of Civil Engineers, Atmospheric Water Management Standards Committee*
[2]*The Environmental & Water Resources Institute*

The Atmospheric Water Management Standards Committee (AWM SC) develops standards for ‘practicing’ atmospheric water management in the areas of precipitation enhancement (SP42), fog dispersal (SP44), and hail suppression (SP39) for adoption by private, for profit, non-profit, country and government organizations for regulatory and other purposes. Practicing does not include research and development of emerging research and development activities at various stages of operational readiness, unless they are demonstrably conducted for an extended period. This talk will include current efforts and highlight their status and solicit ideas or determine the need for new standard practice documents in the weather modification community. We invite all WMA members to support this committee’s efforts.

Acknowledgements: American Society of Civil Engineers, The Environmental & Water Resources Institute

SESSION 3: EVALUATIONS AND ASSESSMENTS
WEDNESDAY, APRIL 30 1:30 – 3:00 PM

Hybrid Seeding Signal Evaluation for Hail Suppression Missions in Southwest Germany

Malte Neuper[1], Marta Nelson[1], Frank Kasparek[1]

[1]*Cloud Seeding Technologies*

Our lifelong quest of validating the impact of seeding operations within fully operational projects is a tough one. Here we present a method based on the sophisticated use of radar data and the application of principles from information theory.

To this point we examined the four-dimensional evolution of airborne cloud base / inflow seeded thunderstorms to demonstrate and classify the changes in the development using the radar volume dataset representing the cell. Data from a C-Band Doppler Radar – located in Southwestern Germany - was used to track different isolated, seeded and non-seeded thunderstorms, while concentrating especially on the development of some bulk properties, which were calculated from the reflectivity data that is supposed to represent the thunderstorm.
Next to more or less common properties like the total volume, the maximum reflectivity, the velocity of a storms' reference point, the total liquid water content, and others - some abstract properties like a 'reflectivity mass' as a reflectivity weighted volume, the height of the center of gravity of the thunderstorms' volume and reflectivity mass and some special ratios were defined with the last parameters being also evaluated in relation to some specific, the convective environment or hail growth zone representing heights like the level of free convection (LFC), the 0°C and the -10°C level, which were extracted from data of operational upper air rawind-soundings.
Apart from a standard conceptional evaluation of a seeding influence we - in a further step - used principles from the information theory. Via for example the Shannon entropy and the Kullback-Leibler Divergence, which is a measure of the difference between two probability distributions, the fundamental, characteristic difference between seeded and unseeded datasets should thus be worked out more objectively.

Acknowledgements: Thanks to the Karlsruhe Institute of Technology (KIT) and Radar-Info.de for the vast access to the radar archive.

Evaluating Precipitation Impacts of Cloud Seeding over the Central Colorado Mountains River Basins (CCMRB) Region using WRF-WxMod®

Michelle Harrold[1], Weiwei Li[1], Sisi Chen[1], Courtney Weeks[1], Sarah Tessendorf[1], Jamie Wolff[1], Tom Blitz[1]

[1]*National Science Foundation | National Center for Atmospheric Research, Boulder, CO, United States*

Ground-based cloud seeding has been conducted across the Central Mountains of Colorado for well over a decade to enhance cold-season precipitation and increase snowmelt-driven water supplies. The Colorado Water Conservation Board is invested in quantifying the effectiveness and optimization potential of the operational cloud seeding program, recognizing that complex topography, atmospheric variability, and seeding opportunity conditions strongly influence outcomes at specific sites. Therefore, the primary goal of this study is to assess the effectiveness of the existing cloud seeding program aimed at augmenting snowpack and subsequent streamflow in the Central Colorado Mountains River Basins (CCMRB). As part of addressing this goal, model simulations are being run to study impacts on precipitation over one season of operational cloud seeding. The 2023–2024 season was selected to be simulated using WRF-WxMod®, where 22 storm periods with documented ground-based seeding operations were simulated at 900-m horizontal grid spacing using a high-resolution ensemble approach designed to quantify uncertainty in both natural and seeded precipitation. The ensemble consists of six control-seed member pairs (12 total members), with perturbations representing variability in (1) large-scale forcing, (2) planetary boundary layer parameterization, and (3) background cloud condensation nuclei concentrations. This modeling framework establishes a quantitative basis for assessing the performance of existing ground-based generators and for identifying opportunities to optimize seeding strategies under varying meteorological conditions within the CCMRB. Key findings regarding simulated precipitation impacts during the 2023–2024 season will be presented.

Acknowledgements: Colorado Water Conservation Board (CWCB)

Investigating the Potential for Winter Orographic Cloud Seeding in Coastal and Interior Regions of the Western U.S.

Sarah Tessendorf[1], Courtney Weeks[1], Meghan Stell[1], Erin Dougherty[1], Trude Eidhammer[1], Nick Dawson[1], Sisi Chen[1], Michelle Harrold[1], Lulin Xue[1], Jamie Wolff[1]

[1]*National Science Foundation | National Center for Atmospheric Research, Research Applications Laboratory, Boulder, CO, United States*

It is important that cloud-seeding programs are designed based upon climatological analyses that take into consideration local conditions, such as the topography and atmospheric conditions that are suitable for seeding (i.e., seeding opportunities). Such studies should identify the characteristics and frequency of local storms suitable for cloud seeding, and then use that information to determine what type of seeding mechanisms (e.g., airborne, ground-based, etc) would be most viable, as well as design where to install or operate seeding facilities. Often, the data needed for such climatological studies is quite limited and/or not available given a lack of routine observations of the relevant parameters (e.g., supercooled liquid water in particular), so a new development has been the use of high-resolution atmospheric model simulations.

In the last five years, multiple cloud seeding climatology studies have been conducted in various western states of the U.S. with the high-resolution (4-km), >40-year Weather Research and Forecasting (WRF) simulation over the conterminous United States (hereafter CONUS404; Rasmussen et al. 2023). The goals have been to investigate local precipitation patterns, amounts and frequencies of supercooled liquid water occurring at temperatures suitable for silver iodide (AgI) nucleation, and the dominant wind regimes that bring precipitating clouds to the region. The second step uses the results of the climatology analysis to design an optimal method to enhance precipitation in the region. The results of the CONUS404 climatology analyses regarding the characteristics and frequency of atmospheric conditions suitable for seeding will be presented, comparing the potential for multiple regions in the western U.S.

Acknowledgements: Roza Irrigation District, Utah Department of Natural Resources, California Energy Commission, Colorado Water Conservation Board/Colorado River District, and Idaho Department of Water Resources

---

Hydrologic Controls on Precipitation-to-Streamflow Conversion: Insights for Cloud Seeding in the Bear and Weber River Basins

Aubrey Dugger[1], Arezoo RafieeiNasab[1], Tom Enzminger[1], Nick Dawson[1], Jamie Wolff[1], Sarah Tessendorf[1]

[1]*National Science Foundation | National Center for Atmospheric Research, Research Applications Laboratory, Boulder, CO, United States*

The Bear and Weber River basins in Utah are critical sources of regional water supply and freshwater inflow to the Great Salt Lake. Through the State of Utah Division of Water Resources SNOWSCAPE campaign, the National Center for Atmospheric Research is modeling hydrologic processes in these basins to better understand snowpack evolution, water partitioning, and runoff efficiency. Our goal is to identify where and under what conditions additional precipitation would most effectively translate into streamflow. We will present findings on the spatial and temporal variability in runoff efficiency across 40 gaged subbasins, highlight the static and dynamic basin characteristics that govern precipitation–streamflow relationships, and offer preliminary insights into implications for cloud seeding strategies.

Acknowledgements: Utah Department of Natural Resources, Division of Water Resources (SNOWSCAPE)

SESSION 3: EVALUATIONS AND ASSESSMENTS

Assessing the winter cloud seeding potential over the White Mountains of Arizona

Frank McDonough[1], James C. Walter[2], John Mejia[1]

[1]*Desert Research Institute, Reno, NV, United States*
[2]*Salt River Project, Tempe, AZ, United States*

Runoff from snowfall across the White Mountains of Arizona is the primary source of water and an important source of hydroelectricity for the city of Phoenix. The National Resources Conservation Services (NRCS) SNOTEL observations shows that the peak yearly median climatological snow water equivalent (SWE) observations across the higher terrain range from 178-mm (7.0”) to 243-mm (9.6”), and 294-cm (116”) of snow is annually observed at the local ski area. There is large variability in the year-to-year precipitation which seems to be tied to the ENSO phase. In addition, the majority of this precipitation is deposited during a few large storms.

To potentially help maximize this critically important snowpack, a winter cloud seeding feasibility study has been conducted. In this study four primary tasks are conducted and the results are presented.

Task 1 includes a 30-year assessment of climate data sets to determine the cloud seeding potential, storm frequency, snowfall and runoff. Next, in Task 2 a set of six winters covering a range of ENSO conditions is simulated using a 1-km horizontal resolution version of the WRF model centered over the high peaks of the White Mountains. The selected winter seasons represent wet and cold winters as well as winters with normal to above normal SWE. The hourly modeled temperatures, winds, stability, cloud microstructures are all characterized and used to create the hourly cloud seeding potential across each of the winters (December 1 – March 31).

In Task 3 a simulated cloud seeding generator network is sited across the mountains using the climatological and modeling analysis. Three multiday storms are selected for simulated seeding. Cloud seeding aerosols are released from the network and tracked as they interact with the model clouds over the White Mountains. The success of the seeding aerosols reaching the supercooled liquid water clouds are quantified. Finally in Task 4 the potential increased precipitation and runoff of a cloud seeding program over the White Mountains are estimated.

Acknowledgements: Salt River Project

SESSION 4: SEEDING AGENTS AND METHODS
WEDNESDAY, APRIL 30 | 3:20 – 4:50 PM

Novel Cloud Seeding Materials: Efficiently Harnessing Water Vapor for Precipitation Enhancement

Linda Zou[1], Sufian Farrah2

[1]*Victoria University, Melbourne, Australia*
[2]*National Centre of Meteorology, Abu Dhabi, United Arab Emirates*

Multiple factors influence precipitation within the hydrological cycle, including atmospheric water vapor concentration, orographic lifting, vegetation, and aerosol emissions from volcanic activity or wildfires. Among these, the presence of atmospheric aerosols—such as volcanic ash, pollen, sea salt, and mineral dust—is a critical driver for raindrop formation. These naturally occurring particles serve as cloud condensation nuclei (CCN), facilitating the condensation of water vapor into fine droplets and initiating the precipitation process. Precipitation is often an unpredictable, random event because it requires the simultaneous presence of sufficient moisture and effective natural nuclei. To address this unpredictability, novel cloud seeding materials can be engineered for ondemand release during field operations to artificially enhance the interaction between seeding agents and cloud systems, thereby increasing the probability of rain formation. This paper reports the successful outcomes of a project from the first cycle of the UAE Research Program for Rain Enhancement Science (UAEREP), which utilized nanotechnology to develop advanced seeding materials for accelerated water condensation. The research covers the design, synthesis, performance characterization and evaluation of hygroscopic core/shell structured particles designed for warm cloud seeding. The results of cloud chamber experiments demonstrated both the water-droplet concentration and the droplet size increased greatly across all size ranges, especially, the concentration of water droplet size between 10 - 25 µm, which is very crucial to the rainfall, caused by the core/shell seeding agents was up to 2.9 times higher than that by NaCl only particles, and 15.5 times higher than that of background without seeding agent. These results positively confirmed it as an effective cloud-seeding materials. Presently, the seeding agent dispensers contain scaled-up novel seeding material have be fabricated and used to evaluate the rain enhancement performance in both open fields. The forthcoming development of glaciogenic seeding materials will be included.

Acknowledgements: UAE Research Program for Rain Enhancement Science

---

Understanding Liquid Propane Seeding: Part I. New Ice Nucleation Parameterization Schemes in WRF

Sisi Chen[1], **Lulin Xue[1]**, Michelle Harrold[1], Sarah Tessendorf[1], Jamie Wolff[1], Darcy Jacobson[1], Nick Dawson[1], Hahns-Peter Marshall[2]

[1]*National Science Foundation | National Center for Atmospheric Research, Boulder, CO, United States*
[2]*Boise State University, Boise, ID, United States*

Liquid propane (LP) cloud seeding can generate ice at relatively warm temperatures where conventional silver iodide (AgI) is less efficient (T > −7 °C), making it a promising tool for winter orographic precipitation enhancement in a warming climate. However, despite intensive research in the 1970s and intermittent operational use since the 1980s, the lack of numerical studies has limited quantitative assessment of LP seeding efficacy and constrained our physical understanding of its impacts on clouds and precipitation. This study addresses that gap by developing and implementing a temperature dependent LP ice nucleation parameterization within the Weather Research and Forecasting (WRF) model. The new scheme is derived from two laboratory studies (Hicks & Vali 1973; Kumai 1982), both quantified ice production as a function of ambient temperature and LP release rate. Idealized simulations over two dimensional mountains are performed to examine the impact of LP seeding on cloud microphysics and precipitation processes under varying thermodynamic and flow conditions. The resulting LP parameterization provides a new modeling capability for explicitly simulating LP seeding impacts and offers guidance for the design, evaluation, and optimization of LP seeding strategies.

Acknowledgements: Idaho Water Resource Board, Idaho Department of Water Resources

---

Understanding Liquid Propane Seeding: Part II. Large-Eddy Simulations over the Camas Prairie

Michelle Harrold[1], Sisi Chen[1], Sarah Tessendorf[1], Lulin Xue[1], Jamie Wolff[1], Darcy Jacobson[1], Nick Dawson[1], and HP Marshall[2]

[1]*National Science Foundation | National Center for Atmospheric Research, Boulder, CO, United States*
[2]*CryoToolBox LLC, Boise, ID, United States*

Liquid propane (LP) cloud seeding is emerging as a promising complement to silver iodide (AgI) for enhancing winter orographic precipitation, particularly under relatively warm conditions where AgI effectiveness is limited (T > −7 °C). The Liquid Propane Experiment (LPX) is currently underway, with deployment and data collection occurring in Idaho during Winter 2024-2025, to evaluate the viability of LP as a cloud seeding agent. While Part I of this study (Chen et al.) introduces and evaluates a new temperature-dependent LP ice nucleation parameterization implemented within the Weather Research and Forecasting (WRF) model, this companion presentation focuses on the application of large-eddy simulations (LES) to characterize the microenvironments of Idaho's Camas Prairie, a region targeted for potential LP seeding operations.

WRF-based LES are used to examine cloud structure, phase partitioning, precipitation processes, and terrain-induced turbulence over the Camas Prairie. Results from a 5-8 January 2024 winter storm case are presented, including comparisons between LES output and available field observations to assess model performance and to improve understanding of the region's natural snowfall processes. Sensitivity experiments incorporating the newly developed LP ice nucleation parameterization are conducted to explore LP plume behavior and seeding impacts under varying atmospheric conditions. Together, these results provide essential baseline knowledge of the Camas Prairie cloud-scale environment and offer guidance for the design, evaluation, and optimization of future LP seeding operations.

Acknowledgements: Idaho Water Resource Board, Idaho Department of Water Resources

---

Utilizing Biogenic Ice Nucleating Proteins for Precipitation Enhancement

Sabina Simjee[1]

[1]*Real Baarish, San Francisco, CA, United States*

Since the 1940s, the field of precipitation enhancement has remained tethered to a stagnant, 70-year-old chemical standard: Silver Iodide (AgI). Legacy, AgI still faces two critical failures in a modern climate context: a heavy-metal environmental footprint and activation ceiling that requires cloud temperatures to drop below −8°C. This leaves a massive volume of atmospheric moisture found in warm winter storms between −2°C and −8°C that is completely unreachable by legacy technology.

Real Baarish is pioneering a transformative transition from inorganic chemistry to atmospheric biology. By integrating high-efficiency, nature-derived ice nucleating proteins (INPs) that naturally mimic cloud processes, we can manufacture water straight from the source. Unlike traditional inorganic materials, our organic seeding agents are biodegradable and trigger precipitation within the thermal dead zone with high nucleation activity at -3°C.

Our research is rooted in pioneering biological work at Boise State University and high-precision aerosol instrumentation from Handix. Our work demonstrates that biological INPs are manufacturable and scalable organic seeding agents that are not only more efficient, but more cost effective compared to legacy AgI.

Furthermore, by utilizing a 100% biodegradable material, we have eliminated the regulatory and environmental barriers that have historically prevented cloud seeding from entering agriculture and municipal drinking water sectors.

As water scarcity and wildfire risks intensify globally, the need for fresh water is critical. Our non-toxic, high-yield seeding agents increase atmospheric precipitation and provide a technical and economic bridge to a secure water future.

SESSION 5: HYGROSCOPIC SEEDING LABORATORY STUDIES AND MODELING

THURSDAY, APRIL 30 | 8:00 – 9:30 AM

SESSION 5: HYGROSCOPIC SEEDING LABORATORY STUDIES AND MODELING

Cloud Chamber Testing of Core/Shell NaCl/TiO2 Seeding Powder

James Simmons[1], Hamed Fahandezh Sadi[1], Suryadev Singh[1], Andrei Vakhtin[2], Kurt Hibert[3], Bruce Boe[3], Youssef Wehbe[4], Corey Bois[5], Steve Krueger[5], Jesse Anderson[1], Raymond Shaw[1], and Will Cantrell[1]

[1]*Michigan Technological University, Houghton, MI, United States*
[2]*Mesa Photonics, Santa Fe, NM, United States*
[3]*Weather Modification International, Fargo, ND, United States*
[4]*National Center of Meteorology, Abu Dhabi, United Arab Emirates*
[5]*University of Utah, Salt Lake City, UT, United States*

The development and refinement of new and existing cloud seeding practices is necessary to ensure precipitation enhancement campaigns are both efficient and effective. Previous experiments in the Pi Cloud Chamber at Michigan Technological University have shown that in-situ seeding of a steady state cloud with milled NaCl powder can stimulate a significant transfer of cloud liquid water into larger droplet sizes. Subsequent experiments were conducted using the recently developed core/shell NaCl/TiO2 (CSNT) seeding powder and at mean temperatures more representative of typical warm cloud seeding candidates (10°C). The experiments show the same characteristic response as the injection of milled NaCl into warmer (20°C) clouds. Further experiments with the injection of CSNT into a subsaturated chamber (75-95% RH) containing no pre-existing cloud resulted in the formation of droplets consistent with a value of roughly 1.28. This result indicates that the CSNT has effectively the same hygroscopic performance as milled NaCl, however the CSNT powder has the advantage of resisting caking which severely inhibits dispersal of the NaCl powder.

Acknowledgements: UAE Rain Enhancement Program

Influence of aerosol loading on the microphysical properties of mixed-phase clouds over the Bay of Bengal: insights from CAIPEEX observations and numerical simulation

Sachin Patade[1], Kedar Tahashildar[1], Aparna Namboothiri[1], Sonali Shete[1], Gayatri Kulkarni[1], Neelam Malap[1], P. Murugavel[1], Thara Prabhakaran[1]

[1]*Indian Institute of Tropical Meteorology, Pune, India*

Aerosols significantly influence the microphysical evolution of mixed-phase convective clouds, yet their effects over oceanic regions remain poorly constrained due to limited in situ observations. This study examines the impact of aerosol loading on the microphysical properties of mixed-phase clouds over the Bay of Bengal using rare airborne measurements from the CAIPEEX Phase II campaign (19 October 2011) combined with high-resolution large-eddy simulations (LES) using the WRF model.

Observations reveal a polluted marine boundary layer with cloud condensation nuclei (CCN) concentrations exceeding 1000 cm^{-3} due to continental aerosol transport. Elevated CCN led to high cloud droplet number concentrations (20–800 cm^{-3}) and small effective radii (<12 μm), suppressing collision–coalescence and delaying warm-rain formation despite high liquid water content (~3 g m^{-3}). An active mixed-phase region was observed around −10 °C, characterized by the coexistence of supercooled liquid water, graupel, and pristine ice crystals, indicating efficient riming and ice growth. Ice number concentrations (10–100 L^{-1}) exceeded estimated INP concentrations by 2–3 orders of magnitude, implying strong secondary ice production (SIP) through processes such as rime splintering, droplet shattering, and ice–ice collisional breakup.

Model simulations reproduce the observed vertical structure and demonstrate pronounced aerosol effects on cloud microphysics. Polluted clouds exhibit ~19% higher liquid water content and ~40% greater ice water

content than clean clouds. Enhanced aerosol loading strengthens depositional growth, aggregation, riming, and snow production, while cloud tops extend to colder temperatures, consistent with aerosol-induced convective invigoration. Ice–ice collisional breakup dominates SIP across a wide temperature range, whereas droplet shattering is more efficient in clean conditions due to larger droplet sizes. Consequently, polluted clouds show stronger ice enhancement and earlier glaciation, with complete glaciation occurring at warmer temperatures (~−18 °C) compared to clean clouds (~−25 °C).

These findings demonstrate that high aerosol loading suppresses warm-rain processes but enhances mixed-phase and ice-phase pathways, shifting precipitation formation toward ice-dominated mechanisms in polluted maritime convection.

Acknowledgements: CAIPEEX

Exploring various warm-cloud seeding strategies using a one-dimensional model

Corey Bois[1], James Simmons[2], Jesse Anderson[2], Hamed Fahandezh Sadi[2], Kadja Flore Gali[2], Suryadev Pratap Singh[2], Andrei Vakhtin[3], Kurt Hibert[4], Bruce Boe[4], Youssef Wehbe[5], Steve Krueger[1], Raymond Shaw[2], Will Cantrell[2]

[1]*University of Utah, Salt Lake City, UT, United States*
[2]*Michigan Technological University, Houghton, MI, United States*
[3]*Mesa Photonics, Santa Fe, NM, United States*
[4]*Weather Modification International, Fargo, ND, United States*
[5]*National Center of Meteorology, Abu Dhabi, United Arab Emirates*

We are exploring the underlying physics which control warm-cloud droplet distribution widening with the cloudy one-dimensional turbulence model (CODT). Simulations are run to replicate experiments in the Michigan Tech Pi-Chamber, as well as taller chambers. The computational speed of the 1D model allows us to simulate a large number of configurations, which helps to extrapolate results from experiments. In the simulations, the distribution of NaCl dry-radii are specified in order to replicate different seeding strategies for various atmospheric aerosol conditions (e.g. clean vs. polluted) and cloud conditions (supersaturation forcings, density/height and presence of collision/coalesence). We discuss the implications of how these controllable/uncontrollable variables could aid in developing targeted in-cloud seeding strategies.

Acknowledgements: This material is based on work supported by the National Center of Meteorology, Abu Dhabi, UAE under the UAE Research Program for Rain Enhancement Science

---

Hygroscopic Seeding with Powders: Insights from the Laboratory

Will Cantrell[1], James Simmons[1], Hamed Fahandezh Sadi[1], Suryadev Singh[1], Andrei Vakhtin[2], Kurt Hibert[3], Bruce Boe[3], Youssef Wehbe[4], Corey Bois[5], Steve Krueger[5], Jesse Anderson[1], and Raymond Shaw[1]

[1]*Michigan Technological University, Houghton, MI, United States*
[2]*Mesa Photonics, Santa Fe, NM, United States*
[3]*Weather Modification International, Fargo, ND, United States*
[4]*National Center of Meteorology, Abu Dhabi, United Arab Emirates*
[5]*University of Utah, Salt Lake City, UT, United States*

Precipitation enhancement by hygroscopic seeding is designed to stimulate formation of a tail of large droplets in a cloud droplet size distribution, which can accelerate the collision-coalescence process in warm clouds, thus triggering precipitation. Experiments in the Michigan Tech Pi Chamber to assess the response of a steady-state, liquid water cloud to in situ injection of a hygroscopic powder have shown dramatic responses, including appearance of large droplets and local enhancement of the liquid water content above the value of the pre-existing cloud. Analysis of the relevant time scales indicates that dry diameter NaCl between 4 and 25 µm would be an effective seeding size, supporting in-cloud hygroscopic seeding as a precipitation enhancement strategy that should be reconsidered alongside traditional cloud-base release paradigms, particularly for warm clouds in arid and semi-arid environments.

Acknowledgements: UAE Rain Enhancement Program

Process-Level Investigation of Hygroscopic Seeding Impacts on Mixed-Phase Cloud Evolution

Gayatri Kulkarni[1], Sachin Patade[1], Neelam Malap[1], Thara Prabhakaran[1]

[1]*Indian Institute of Tropical Meteorology, Pune, India*

This study investigates the microphysical and dynamical impacts of hygroscopic cloud seeding on deep convective clouds using high-resolution WRF–SBM simulations with explicit process-rate diagnostics. Idealized sounding-forced experiments contrasting low (100 cm^{-3}) and high (6000 cm^{-3}) CCN conditions are performed to isolate aerosol effects under identical thermodynamic forcing. Results show that enhanced CCN delays early warm-rain formation while increasing supercooled liquid water and promoting stronger mixed-phase. Process-rate analysis reveals intensified condensation, freezing, riming, and aggregation in high-CCN simulations, leading to enhanced ice-phase growth. Despite increased condensate loading, diagnosed buoyancy remains higher in the polluted case, indicating that latent heating associated with warm and cold microphysical processes outweighs the negative loading effect. This net buoyancy enhancement results in stronger and more persistent updrafts, prolonged mixed-phase development, and delayed but enhanced precipitation. The findings provide mechanistic evidence that hygroscopic seeding can invigorate convection through coupled microphysical–dynamical pathways.

SESSION 6: PROJECT UPDATES AND EVALUATIONS
THURSDAY, APRIL 30 | 10:50 – 12:10 AM

Introduction of SNOWSCAPE: The Seeded and Natural Orographic Winter Storms and Catchment Processes Evaluation Project

Nick Dawson[1], P. Brooks2, A. Dugger[1], P. Golden[6], G. Hallar[2], J. Horel[2], J. Jennings[5], J. Mace[2], J. Meyer[3], B. Pokharel[3], M. Skiles[2], J. Smith[4], A. Stansfield[2], J. Steenburgh[2], K. Suski[4], S. Tessendorf[1], P. Veals[2], D. Yorty[4]

[1]*National Science Foundation | National Center for Atmospheric Research, Boulder, CO, United States*
[2]*University of Utah, Salt Lake City, UT, United States*
[3]*Utah State University, Logan, UT, United States*
[4]*RainMaker Technology Corporation, El Segundo, CA, United States*
[5]*Utah Division of Water Resources, Salt Lake City, UT, United States*
[6]*Heritage Environmental Consultants, CO, United States*

Utah's weather modification program has been operational since the 1970s. Prior Target-Control benefit analysis has estimated precipitation increases of 8-28%, yet a coupled weather-hydrology modeling evaluation has never been performed. The Seeded and Natural Orographic Winter Storms and Catchment Processes Evaluation Project (SNOWSCAPE) is an NSF NCAR, state, university, and private collaboration to collect observations in the northern Wasatch Mountains near Ogden, Utah from January to early March 2026. The primary goal is to use collected data to evaluate and improve a coupled WRF-WxMod and WRF-Hydro system for a modeled evaluation of the northeastern Utah weather modification program across three historic water years. Additionally, we aim to improve understanding of natural precipitation processes as well as identify ways to optimize precipitation gains in Utah's northeastern projects. Numerous instruments were deployed such as two scanning X-band radars (DOW's), MRRs, MWRs, ceiliometers, precipitation gauges, aerosol instruments, radiosondes (balloon and drone), streamflow gauges, and snow energy balance systems. Instruments are primarily located along a southwest to northeast transect from Antelope Island to Huntsville, which aligns with the primary flow direction in the area. This presentation will provide an overview of the campaign, timeline, lessons learned, and an early characterization of Intensive Observing Periods based on radiosondes.

Thompson and Griffith, 2012: Seven Years of Weather Modification in Central and Southern Utah, J. Wea. Mod., 13(1), 141-149. DOI:10.54782/jwm.v13i1.45

Acknowledgements: Utah Division of Water Resources

Operational Overview and Evaluation Framework of Cloud Seeding in Korea

Sun Kim[1], Sungju Lee[1], SooHui Jeon[1], HyeMin Shin[1], Kang-Min Kim[1], WonKyung Lee1, Ki-Ho Chang, Joo-Wan Cha[2], Yun-Kyu Lim[2], HaeJung Koo[2], Yonghun Ro[2], Young-Suk Oh[2], Miloskav Belorid[2], Min-Hoo Kim[2], Hyunjun Hwang[2], A-reum Ko[2], Yujin Kim[2], JoongHyun Jo[2], Munseok Lee[2], Sunguk Song[2], In-Gyum Kim[2]

[1]*Sunny Air Inc., Seoul, South Korea*
[2]*National Institute of Meteorological Sciences, Jeju-do, South Korea*

Cloud seeding activities in Korea have progressed from early experimental studies to 5 year operational verification program. The program started with 2 King Air C90A aircrafts equipped with BIP flare racks and ejectable flare racks, and Cessna 208A Caravan, equipped with salt powder dispenser was added to the fleet. Prior to each seeding operation, numerical weather prediction using the WRF model is conducted to assess atmospheric conditions favorable for seeding and to estimate potential impacts of the operation. Following each operation, seeding effects are evaluated through an integrated verification framework combining numerical model analysis, radar observations, and rainwater sampling with ionic composition analysis. Rainwater samples collected during precipitation events are analyzed to identify potential signatures of seeding materials, while radar observations and model analyses are used to examine spatial and temporal characteristics of precipitation responses associated with seeding operations.

Long-term statistical evaluations for the cloud seeding effects are commonly used in many countries, but the Korean cloud seeding program focus on event-based verification for individual experiments. This approach enables detailed investigation of seeding influenced areas and provides practical feedback for improving operational strategies.

These activities shall further enhance the knowledge and technology of weather modification in Korea, expanding to full operational stage in the near future.

Acknowledgements: Sunny Air and National Institute of Meteorological Sciences, South Korea

---

Using Radiometer Observations of Utah Wintertime Cloud Conditions to Calibrate and Evaluate an Operational High-Resolution Numerical Forecast Model

Jonathan Meyer[1,2], Binod Pokharel[1,2], Casey Olson[1,2], Jonathan Jennings[3]

SESSION 6: PROJECT UPDATES AND EVALUATIONS

[1]*Utah Climate Center, Logan, UT, United States*
[2]*Utah State University Department of Plants, Soils, and Climate, Logan, UT, United States*
[3]*Utah Division of Water Resources, Salt Lake City, UT, United States*

Radiometer observations of wintertime cloud conditions in northern Utah are used to evaluate the ability of a high-resolution numerical forecast model to simulate the meteorological environment. Over the 2025/'26 winter season, the Utah Climate Center provided real-time operational forecast guidance in support of the Utah Division of Water Resources cloud seeding operations. Offering increased horizontal and vertical resolution, as well as customizable model physics, an operational configuration of the Weather Research and Forecast (WRF) model downscaled the High-Resolution Rapid Refresh (HRRR) parent model. Here, we present results from a model physics calibration phase, which tested the sensitivity of forecast cloud conditions to various model physics suites available within the WRF framework. Additionally, we compare the model's ability to capture the observed nature of cloud liquid water content and other cloud-related parameters throughout northern Utah during the SNOWSCAPE field campaign.

Acknowledgements: Utah Division of Water Resources

Evaluating Cloud Liquid Water over Utah's Mountain Ranges: Implications for Cloud Seeding Operations

Binod Pokharel[1], Casey Olson[1], Jonathan Meyer[1], Jonathan Jennings[2]

[1]*Utah State University, Logan, UT, United States*
[2]*Utah Division of Water Resources, Salt Lake City, UT, United States*

Microwave radiometers have been deployed across Utah's mountain ranges to measure cloud liquid water (CLW), a critical parameter for cloud seeding operations. A radiometer installed in Cache Valley, Utah, collected CLW data over two consecutive winters (from winter of 2024–2025), and three additional radiometers were deployed during the winter of 2025–2026. Of these, two are positioned in northern Utah in support of the Seeded and Natural Orographic Winter Storms and Catchment Processes Evaluation (SNOWSCAPE) project, while the third targets the La Sal Mountains in eastern Utah. This presentation examines the frequency and magnitude of CLW across the different mountain ranges and evaluates the performance of operational forecast models used for Utah cloud seeding. Specifically, CLW estimates from the NAM, and HRRR downscaled WRF models are compared with radiometer observations to assess forecast accuracy for CLW and precipitation. This evaluation focuses on the Utah forecast model operated by the Utah Climate Center, as accurate CLW prediction is essential for effective cloud seeding decision-making. Although the winter of 2025–2026 was among the driest and warmest on record for Utah, the forecast products demonstrated here remain valuable for both operational cloud seeding and the SNOWSCAPE program. The presentation will also highlight CLW variability in relation to synoptic conditions observed during the SNOWSCAPE campaign, illustrating contrasting atmospheric environments associated with high and low CLW episodes.

Acknowledgements: Utah Division of Water Resources

SESSION 7: EMERGING TECHNOLOGIES AND AI APPLICATIONS IN WEATHER MODIFICATION
THURSDAY, APRIL 30 | 1:30 – 3:00 PM

Advancing Cloud Seeding Science with Dual-Polarization Radar Signatures and AI

Mike Dixon[1], Roelof Burger[2]
[1]*Echo Science Works, United States*

[2]*North-West University, South Africa*

This project, funded by the UAE Research Program for Rain Enhancement Science (UAEREP), aims to advance convective cloud seeding science by integrating dual-polarization radar microphysics, storm-object tracking, and physics-guided artificial intelligence. We will modernize the TITAN/LROSE storm identification and tracking system to ingest full dual-polarization radar data and generate enhanced TITAN storm-object properties in open NetCDF formats.

Dual-polarization fields (ZDR, KDP, ρHV, and particle ID) should provide microphysical insights beyond traditional reflectivity and velocity, enabling new emergent properties such as hydrometeor fractions, ZDR/KDP columns, vertical hydrometeor phase structure, and improved quantitative precipitation estimates. These physically meaningful descriptors will form the foundation for AI-supported operations and evaluation.

We aim to use AI techniques to (1) bias-correct short-term TITAN nowcasts, (2) predict probabilistic “seedability windows” based on storm evolution, and (3) implement anomaly-based evaluation by learning the typical evolution of unseeded storms and identifying departures observed in seeded cases. Results will be TITAN storm-object based, interpretable, and operationally available. The expected outcome is a physically grounded, statistically defensible framework for improving targeting decisions and quantifying seeding impacts.

Acknowledgements: UAE Research Program for Rain Enhancement Science

---

Building an Operational AI-Based Cloud Seedability System: Scalable Deployment, High Uptime, and Operational Decision Support

Duncan Axisa[1]

[1]*Atmo Inc, San Francisco, CA, United States*

The use of data in weather modification has evolved from manual interpretation toward real-time guidance and more automated workflows. Early systems demonstrated how thresholding in situ measurements could be used to identify cloud seedability and support pilot decision-making in real time. Today, this approach is extending into data-driven systems that combine multiple data sources to support targeting decisions and enable more scalable operations, including future use with uncrewed aerial systems.

This work presents the development of an AI-based cloud seedability framework designed for operational use. The system brings together model output and physically based indicators into a consistent workflow, with the capability to incorporate observational data as it becomes available. It includes data ingestion, processing, training on historical cases, and delivery through a user interface built for operational meteorologists.

A key focus of this work is the development of a reliable operational stack. The system is designed for continuous use, with greater than 99% uptime, and can be deployed rapidly across new domains. This enables consistent performance in real-world settings and supports time-sensitive decision-making.

Examples from the Bear River Basin, Utah, and Pendleton, Oregon show how the system is applied to winter orographic clouds, with a focus on improving targeting confidence and reducing false positives. The same framework has also been adapted to a tropical environment over the Philippines, where it is used by the national weather service to support precipitation forecasting.

A key part of this effort is how the information is presented to the user. The interface is designed to be clear, intuitive, and aligned with how meteorologists make decisions in real time. Overall, this work reflects a shift from standalone threshold-based tools toward integrated operational systems, where data, models, and workflows are closely linked to support consistent and informed decision-making.

Case-Study Analysis of Ionization-Induced Wintertime Precipitation Enhancement in the La Sal Mountains, UT

Dr. Jeffrey Chagnon[1], Rutuja Dongre[1], Scott Morris[1], Taylor Gresham[1]

[1]*Rain Enhancement Technologies, Naples, FL, United States*

Rain Enhancement Technologies (RET) has deployed and is operating a ground-based ionization system—the Weather Enhancement Technology Array (WETA)---in the La Sal Mountain area of Utah. This presentation reports preliminary results from the 2025-2026 winter season (November through March), demonstrating measurable precipitation enhancement through comprehensive observational analysis.

Evidence for enhancement is presented through multi-source data assimilation, including snowpack sensors (SNOTEL), WSR-88D radar, radiometer observations, and aerosol modeling using NOAA's HYSPLIT model. Aerosol modeling provides visual evidence that WETA directly influences cloud activity and reactions, with modeled plume characteristics spatially and temporally correlated to observed precipitation patterns. Storm-by-storm analysis reveals that precipitation cells consistently intensified and persisted longer over the La Sal Mountains treatment area. Radar analysis offers insights into cloud microphysical responses, while ground-based measurements quantify snowpack accumulation differences between treatment and control sites.

Ongoing statistical evaluation benchmarks the 2025-2026 season against the five driest years of the past twelve years. Early results from this analysis indicate precipitation enhancement exceeding 20%. This work represents one of the first comprehensive field evaluations of ground-based ionization technology for winter precipitation enhancement, offering both operational insights and scientific understanding of ionization effects on orographic precipitation processes.

Electrostatic Fog Mitigation Using the FREA System: Pilot Results and a Framework for Quantifying Ionization-Induced Droplet Coalescence

Taylor Gresham[1], Scott Morris[1], Jeffrey Chagnon[1], Rutuja Dongre[1], Emily Powell[1]

[1]*Rain Enhancement Technologies, Naples, FL, United States*

Rain Enhancement Technologies (RET) presents initial qualitative findings and a quantitative evaluation framework for the Fog Removal by Electric Activity (FREA) system, a scaled ground-based ionization array designed to mitigate radiation fog. The FREA system generates localized corona discharge points that ionize passing air particles, increasing the probability of water coalescence.

In September 2025, RET conducted a proof-of-concept field trial near Sydney, Australia — the first real-world evaluation of the FREA system under natural fog conditions. These trials assessed system feasibility, operational constraints, and low-cost instrumentation suitability for detecting fog microphysical response. Key observations included accelerated fog dissipation relative to surrounding untreated areas and rapid fog reformation following system deactivation, offering encouraging preliminary evidence of an ionization-driven effect.

Building on these results, RET is advancing toward structured field trials employing a treatment-and-control site design with co-located instrumentation. This includes optical particle counters (OPC) for liquid water content, forward-scattering atmospheric visibility sensors (for Meteorological Optical Range, MOR), meteorological stations, and supplemental wind and soil moisture sensors. This framework is designed to quantify the effective dispersal radius, measure fog dissipation rates, and characterize the microphysical properties that govern coalescence efficiency. A difference-in-differences statistical approach will isolate treatment effects from ambient meteorological variability.

This presentation outlines the scientific basis for FREA, lessons learned from the Australian pilot, and the instrumentation and evaluation methodology informing RET's ongoing research program.

DISCUSSION PANEL 2

ADVANCING CAPABILITIES: AI AND MACHINE LEARNING IN WEATHER MODIFICATION

THURSDAY, APRIL 30 | 3:20 – 4:20 PM

SESSION 8: ATMOSPHERIC VARIABILITY, AEROSOL CHARACTERIZATION, AND MEASUREMENT ADVANCES

FRIDAY, MAY 1 | 09:30 – 11:00 AM

A 30-Year Spatiotemporal Analysis of Urban Heat Islands and Its Health Economic Consequences in Khulna, Bangladesh

Halima Akter[1], Irteja Hasan[1]

[1]*University of Barishal, Barishal, Bangladesh*

Rapid urbanization has intensified the Urban Heat Island (UHI) effect in many hot regions, posing serious environmental, health, and economic challenges. From 1995 to 2025, the spatiotemporal dynamics of UHI in Bangladesh's Khulna City Corporation (KCC) are investigated in this study. It examines variations in land surface temperature (LST), changes in land use and cover (LULC), and the corresponding effects on the economy and public health. Thermal bands were used to determine LST, the Normalized Difference Vegetation Index (NDVI) was used to evaluate vegetation dynamics, and a Support Vector Machine (SVM) algorithm was used to classify LULC using multi-temporal Landsat imagery (Landsat-5 and Landsat-8). Urban and surrounding rural surface temperatures were compared to determine the intensity of the UHI. The findings demonstrate the fast growth of cities, with built-up areas rising from roughly 10% in 1995 to over 32% in 2025, while vegetation cover decreased from 72% to 45%. In 2025, 67% of the city was covered by areas above 40°C, up from 44% in 2015. The UHI intensity progressively rose to almost 12°C. According to statistical analysis, there is a strong positive correlation ($r \approx 0.99$) between LST and UHI intensity and a negative correlation ($r = -0.25$) between vegetation cover and LST. Increased heat-related health risks are found in regression results, especially for outdoor workers (OR = 5.99, $p < 0.001$) and older populations (OR = 3.46, $p < 0.001$). Significant livestock mortality (OR = 29.35, $p < 0.001$) and income loss (47.7%) were caused by heat stress. The results highlight the critical need for targeted public health interventions, increased green infrastructure, and climate-responsive urban planning to improve resilience in coastal cities like Khulna that are rapidly urbanizing.

Cloud Seeding Aerosol Characterization

Xiaoliang Wang[1], Jesse Juchtzer[1], Bjoern Bingham[1], Patrick Melarkey[1], Craig Hall[1], Frank McDonough[1]

[1]*Desert Research Institute, Reno, NV, United States*

SESSION 8: ATMOSPHERIC VARIABILITY, AEROSOL CHARACTERIZATION, AND MEASUREMENT ADVANCES

Cloud seeding is widely used to enhance precipitation, most commonly through the dispersion of silver iodide (AgI) particles. Many ground-based generators have been deployed across the U.S. However, the influence of cloud seeding solution (CSS) formulation, generator design, and operational settings on particle generation, as well as the physical and chemical properties of the resulting particles, are routinely or systematically evaluated. This lack of characterization introduces significant uncertainties in generator performance and overall seeding effectiveness. Moreover, recent numerical studies of cloud seeding often rely on assumed particle size distributions, highlighting the need for accurate measurement. Comprehensive characterization of aerosol properties under real-world operating conditions is therefore essential for both optimizing generator performance and improving the reliability of cloud seeding models.

In this study, an aerosol measurement system was developed and deployed to characterize cloud seeding particles, including their size distributions, generation rates, and chemical compositions. Measurements were conducted for a Desert Research Institute (DRI) ground generator, a manual generator, and pyrotechnic flares. Particles emitted from the DRI ground generator exhibited unimodal size distributions, with peak diameter increasing from 110 nm to 145 nm as the CSS flowrate increased from 14.6 to 43.4 mL/min. Correspondingly, particle generation rates increased from 8.4×10^{13} to 2.1×10^{14} particle/min. The manual generator produced particles with a peak diameter of 150 nm, while flare-generated particles displayed bimodal distributions, with peaks near 250-350 nm and 650 nm.

Chemical analysis indicated that particles from the DRI and manual generators were dominated by AgI, with a molar Ag/I ratio close to unity. In contrast, particles generated by flares exhibited more complex compositions, with elevated fractions of additional elements and ions and a lower Ag/I molar ratio of 0.28.

These findings provide critical data for improving cloud seeding models and offer practical insights for optimizing generator design and operational parameters.

Acknowledgements: DRI- State of Nevada Cloud Seeding Program (SB99 & SB6 Funding Support) and the DRI VPR Office of Innovation Research Program Seed Funds

---

Coping with High Precipitation Variability

Dr. Arquimedes Ruíz-Columbie[1]

[1]*Texas Tech University, Lubbock, TX, United States*

Using National Centers for Environmental Information (NCEI) ground-based precipitation data and the prescribed Target versus Control Method for the evaluation of operational cloud seeding projects, a counterfactual analysis is presented to reassess the existence of a long-term signal of precipitation modification in the Panhandle Water Conservation District Target Area of the Texas Panhandle, which has been in operation for the last 25 years. Extensions to other Texas projects are also explored.

Acknowledgements: Texas Weather Modification Association

Beyond the Droplet: Using the Cloud Condensation Nuclei Counter to Characterize Seeding Materials and Determine Nuclei Characteristics Through Dual-Chambers and PCVI Integration

Kimberly Dill[1], Darrel Baumgardner[1], Dagen Hughes[1]
[1]*Droplet Measurement Technologies /Envea Group, Longmont, CO, United States*

The Cloud Condensation Nuclei (CCN) counter has traditionally been utilized as the primary tool for understanding droplet activation in both ground-based and airborne applications. Using a diffusion chamber for activation and an optical spectrometer to count and size, the CCN allows the user to determine activation efficiency for a given set of ambient conditions. With the addition of a secondary chamber in the dual-chamber CCN-200, the system allows for a control sample along with a modified sample. This provides the user with the opportunity to characterize the effectiveness of hygroscopic seeding materials through comparisons between the seeded air and that of what would have been realized with only ambient CCN available for activation; a direct comparison not possible in uncontrolled environments.

While a powerful tool on its own, the newly developed CCN-200 with Pumped Counterflow Virtual Impactor (PCVI), opens up a new realm of cloud-aerosol interaction analyses. This system provides the capability for additional aerosol instrumentation to be integrated into the chamber outflow allowing for further characterization of the aerosol nuclei including black carbon and bioaerosols. This tool may allow for characterization of residual carbon from the flare burns or provide a better understanding of what aerosol types are present and how they are impacting droplet activation efficiency.

A Comparison of Nucleation Pathways for some Dispersing Systems

Thomas DeFelice[1,2]

[1]American Society of Civil Engineers, Atmospheric Water Management Standards Committee
[2]The Environmental & Water Resources Institute

This presentation will explore the nucleation pathway of the dispersed seeding agent (aerosol or nuclei) to precipitation sized hydrometeors from conventional versus emerging and new technology dispensing systems. It will highlight possible environmental deposition and possible social aspects.

POSTER SESSION

THURSDAY, APRIL 30 | 09:50 – 10:50 AM

Sampling-Based Model Predictive Control for Event-Scale Rainfall Regulation

Yang Bai[1], Binquan Qiu[1], Masaki Ogura[1]

[1]*Hiroshima University, Japan*

Extreme rainfall events are major triggers of natural hazards such as floods and landslides, posing serious threats to human safety and socio-economic systems. While rainfall intervention has long been studied, most existing approaches rely either on empirical climatological methods or on control strategies built upon simplified atmospheric models, which limit their applicability to realistic, hih-dimensional weather systems.

This work investigates an event-scale precipitation control framework that directly operates on high-fidelity numerical weather models without model simplification. Offshore drag-inducing structures are employed as control actuators: distributed resistance elements deployed over the ocean introduce additional aerodynamic drag, perturbing wind fields and influencing moisture transport and precipitation formation. The control problem is formulated as designing time-varying spatial layouts of offshore resistance elements to reduce accumulated precipitation over a target region.

To address the resulting high-dimensional and nonlinear optimization problem, we develop a sampling-based model predictive control (SBMPC) framework. A wind-informed Centroidal Voronoi Tessellation (CVT)–based spatial prior is introduced to improve sampling efficiency, while the high-fidelity numerical weather prediction model is embedded directly into the control loop.

The framework is evaluated using ensemble numerical experiments on the extreme rainfall event over Kyushu, Japan (August 10–13, 2021) using the SCALE-RM model on the Fugaku supercomputer. Results show that the proposed method consistently reduces 72-hour accumulated precipitation, achieving an average reduction of 21.13% compared with the uncontrolled ensemble.

Case Studies of Warm Season Cloud Seeding Experiments in Korea

Kang-Min Kim[1], SungJu Lee[1], SooHui Jeon[1], Hyemin Shin[1], Wonkyung Lee[1], Hun Hong[1], A-Hyun Lee[1], Ki-Ho Chang[2], Yun-Kyu Lim[2], Yonghun Ro[2], A-Reum Ko[2], Yujin Kim[2], JoongHyun Jo[2], Munseok Lee[2], Sunguk Song[2]

[1]*Sunny Air Inc., Seoul, South Korea*
[2]*National Institute of Meteorological Sciences, Jeju-do, South Korea*

This study presents several case studies of warm-season cloud seeding experiments conducted in Korea to evaluate precipitation enhancement under operational conditions. Seeding experiments were designed using numerical weather prediction with the WRF model to identify favorable atmospheric environments and estimate potential seeding impacts. Based on the model guidance, aircraft seeding operations were conducted using appropriate seeding agents depending on atmospheric conditions.

The operational procedures, including flight paths and seeding material selection, were adapted according to cloud characteristics and thermodynamic environments. Following the operations, precipitation responses were analyzed using radar observations and surface rainfall measurements to investigate potential changes in precipitation distribution and intensity. Additional numerical simulations for seeded and non-seeded cases were conducted to examine potential differences in precipitation development associated with seeding operations. The simuation results were compared with radar observations to evaluate the spatial and temporal characteristics of precipitation changes in target areas.

To further examine the possible seeding signatures in precipitation, rainwater samples collected during precipitation events were analyzed for ionic composition. The results indicate increases in specific ionic components associated with seeding materials, providing supporting evidence of seeding influence in selected cases.

Several representative cases, including one experiment conducted in 2024 and two experiments during drought conditions in the Gangneung region in 2025, are presented in this poster. The integrated analysis combining numerical modeling, seeded and non-seeded simulations, radar observations, operational flight data, and rainwater chemistry provides a comprehensive framework for evaluating warm-season cloud seeding experiments in Korea and contributes to the development of future operational weather modification program strategy.

Acknowledgements: Sunny Air Inc. and the National Institute of Meteorological Sciences, Korea

---

Numerical experiments of cloud seeding for mitigating localization of heavy rainfall: a case study of Mesoscale Convective System in Japan

Jacqueline Mbugua[1], Yusuke Hiraga[1], Shunji Kotsuki[2,3,] Yoshiharu Suzuki[4], Shu-Hua Chen[5], Atsushi Hamada[2,6,] Kazuaki Yasunaga[6], Takuya Funatomi[7]

[1]*Department of Civil and Environmental Engineering, Tohoku University, Sendai, Japan*
[2]*Center for Environmental Remote Sensing, Chiba University, Chiba, Japan*
[3]*Institute for Advanced Academic Research, Chiba University, Chiba, Japan*
[4]*Department of Civil and Environmental Engineering, Hosei University, Tokyo, Japan*
[5]*Department of Land, Air and Water Resources, University of California, Davis, CA, United States*
[6]*Faculty of Sustainable Design, University of Toyama, Toyama, Japan*
[7]*Academic Center for Computing and Media Studies, Kyoto University, Kyoto, Japan*

This study investigated the potential of cloud seeding to mitigate extreme rainfall localization (i.e., overseeding) associated with mesoscale convective systems in Japan. Using a numerical weather prediction model, we conducted cloud seeding experiments by artificially increasing ice nuclei concentrations in a double-moment microphysics scheme for the heavy rainfall event in Hiroshima Prefecture, Japan, in August 2014. We examined the sensitivity of rainfall changes to altitude and area of the seeding. The results showed that seeding in the mid–upper troposphere (7.2–8.6 km), where air temperature ranged from −22 to −12 °C, resulted in the most pronounced changes in rainfall amount. At these levels, high supercooled cloud water content and strong updrafts favoured heterogeneous freezing, resulting in a depletion of moisture and suppression of graupel growth. The cloud seeding led to reduced rainfall within the heavy rainfall region and increased rainfall downwind, demonstrating the hypothesized dispersal mechanism of “overseeding”. Expanding the seeding to cover the upstream region of the heavy rainfall area had a greater impact than increasing vertical thickness of the seeding. The most effective seeding configuration (24 km × 24 km area at 7.2 km) achieved an 11.5 % decrease in area-averaged 3-h accumulated rainfall and a maximum reduction of 32 % in 3-h accumulated rainfall over the heavy rainfall region. Future work should consider more realistic representations of seeding substance (i.e., transport, dispersion, and interactions) and explore a wider range of rainfall events to generalize the applicability of this approach.

Acknowledgements: This research has been supported by the Japan Science and Technology Agency, Moonshot Research and Development Program (grant no. JPMJMS2389-5-3). This work was supported by “Joint Usage/Research Center for Interdisciplinary Large-scale Information Infrastructures (JHPCN)” and “High Performance Computing Infrastructure (HPCI)” in Japan (Project ID: jh240013).

POSTER SESSION

Data-Driven Microphysical Modeling and Remote Sensing of Snowfall Enhancement via Cloud Seeding for Water Resource Augmentation

Ghazal Mehdizadeh[1], Ehsan Erfani[1], Frank McDonough[1], Farnaz Hosseinpour[1]

[1]*Desert Research Institute, Reno, NV, United States*

Cloud seeding has been widely used to enhance precipitation in water limited regions, yet its physical effectiveness remains partially understood. Many operational programs depend on sparse observations or simplified assumptions, limiting the ability to assess how seeding influences cloud microphysics. This research addresses that gap by integrating high resolution microphysical modeling with satellite based remote sensing to evaluate glaciogenic cloud seeding in the western United States. The goal is to clarify how seeded particles interact with cloud systems and identify the atmospheric conditions most conducive to increasing snowfall.

A core component of the study is the Snow Growth Model for Rimed Snowfall (SGMR), which simulates key ice phase processes including silver iodide nucleation, vapor deposition, aggregation, and riming. The model was first applied to five cloud seeding events in the Lake Tahoe area using inputs from MERRA 2 and CERES reanalysis products. It generated detailed estimates of snowfall rates, particle sizes, and ice crystal concentrations for both seeded and unseeded scenarios. The analysis was then expanded to events across Lake Tahoe, the Santa Rosa Range, and the Ruby Mountains. These cases employed ground based silver iodide generators, and atmospheric responses were evaluated using GOES R satellite observations and radar reflectivity mosaics. Key spectral channels from the Advanced Baseline Imager were used to assess cloud top temperatures, optical thickness, cloud phase, and moisture structure. Results from both modeling and remote sensing show that cloud seeding effectiveness depends strongly on pre existing atmospheric conditions. Enhanced snowfall occurred primarily when clouds contained abundant supercooled liquid water, colder cloud tops, and moist mid to upper tropospheric layers. Events lacking these characteristics showed minimal response. Overall, this work demonstrates the value of combining microphysical modeling with geostationary satellite observations to identify favorable seeding conditions and improve the design and evaluation of weather modification strategies.

Enhancing Long Lead Cloud Seeding Guidance with High Resolution Downscaled Sub-Seasonal Forecasts over Utah

Casey Olson[1,2,] Binod Pokharel[1,2], Jonathan Meyer[1,2]

[1]*Utah State University, Logan UT, United States*
[2]*Utah Climate Center, Logan, UT, United States*

Sub-seasonal forecasts can represent large-scale atmospheric patterns reasonably well, but their skill diminishes at regional or local scales. To improve forecast utility for cloud seeding operations, we developed a dynamically downscaled seasonal forecast system at convection-permitting (4 km) resolution focused on the state of Utah. This pilot study evaluates improvements to the skill of sub-seasonal forecasts of vertically integrated liquid water (QVIL) produced through dynamical downscaling. The downscaling uses the National Centers for Environmental Prediction's Climate Forecast System Version 2 (CFSv2), which provides deterministic forecasts up to nine months at 1° horizontal resolution. Utah's complex terrain limits predictive skill at this native resolution because key land–atmosphere processes are underrepresented. To address this limitation, the Weather Research and Forecasting (WRF) model is used to generate a one-way nested configuration consisting of a 12 km outer domain covering the western United States and a 4 km inner domain over Utah. Forecast skill for weekly sub-seasonal QVIL is evaluated by comparing downscaled forecasts with microwave radiometer observations using a confusion-matrix framework. Results from this pilot effort provide an initial assessment of whether high-resolution, dynamically downscaled S2S forecasts can enhance long lead guidance for cloud seeding operations in mountainous terrain.

Acknowledgements: Utah Climate Center

Towards Event-Scale Control of Precipitation via Sampling-Based Optimization

Qiuyi Ren[1](China), Yang Bai[1], Masaki Ogura[1]

[1]*Hiroshima University, Japan*

Severe rainfall events can cause significant human and economic losses, creating a strong need for control-oriented approaches to precipitation reduction. In this study, we propose a sampling-based model predictive control (SBMPC) framework for precipitation management based on a numerical weather prediction (NWP) model.

Within this framework, accumulated precipitation over a target land region is defined as the control objective, while the control input is the placement of offshore drag-inducing structures. By adjusting the locations of these structures, the local wind field and moisture transport can be modified, thereby influencing subsequent precipitation development. Because atmospheric processes are highly nonlinear, uncertain, and sensitive to initial conditions, we adopt a receding-horizon strategy in which candidate control actions are repeatedly evaluated at each control time using the latest atmospheric state.

Specifically, at each control step, multiple candidate structure configurations are generated and evaluated using the NWP model. Their predicted effects on precipitation over the target region are then compared, and the best candidate is selected for application during the next control interval. This derivative-free sampling strategy is suitable for a high-dimensional, nonconvex, and computationally expensive control problem.

The proposed framework is evaluated for the Kyushu heavy rainfall event of August 10–13, 2021, using SCALE-RM (SCALE library v5.5.4) on the Fugaku supercomputer. The target region is defined over northern Kyushu, Japan, and 21 sail-like drag structures are placed over the ocean. In the model, these structures are represented as additional aerodynamic drag applied from the surface up to 300 m altitude. Results from controlled and baseline ensemble simulations indicate that the proposed SBMPC framework can reduce accumulated precipitation over the target region and provides a practical foundation for weather-control studies under uncertainty.

Glaciogenic Cloud Seeding Potential in Southwest Montana

Michelle Harrold[1], Sarah Tessendorf[1], Maria Frediani[1], Kyoko Ikeda[1], Meghan Stell[2], Courtney Weeks[1], Jamie Wolff[1], Lulin Xue[1]

[1]*National Science Foundation | National Center for Atmospheric Research, Boulder, CO, United States*
[2]*Colorado State University, Fort Collins, CO, United States*

The Montana Department of Natural Resources and Conservation (DNRC) is interested in exploring the feasibility of glaciogenic cloud seeding as a method to augment snowpack and subsequent streamflow in southwestern Montana. Following a climatological analysis of cloud and precipitation characteristics in the region, the Big Hole Basin was identified as one area of interest for an initial feasibility and program design study. This climatology study incorporated SNOTEL precipitation data alongside the CONUS404 dataset—a high-resolution, 40+ year dynamically downscaled dataset—under both current and projected future climate conditions. Key findings from this analysis informed the optimal timing and placement of ground-based and airborne cloud seeding operations, leading to the development of a preliminary program design. To assess the potential effectiveness of this design, multiple case studies were simulated using WRF-WxMod, a state-of-the-art numerical model developed at NSF

NCAR that simulate the physics of cloud seeding with silver iodide. Various ground-based and airborne seeding scenarios were evaluated to estimate potential snowpack increases across the Big Hole Basin. This presentation will summarize key results, including a refined program design based on results from the modeling component of this study.

Acknowledgements: Montana Department of Natural Resources and Conservation (DNRC)