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# Rethinking water security in a warming climate: rainfall enhancement as an innovative augmentation technique

Youssef Wehbe[1], Steve Griffiths[2]✉, Alya Al Mazrouei[1], Omar Al Yazeedi[1] and Abdulla Al Mandous[1]

Rainfall enhancement has historically been overlooked as a key component of sustainability and climate change adaptation strategies. In this comment, we argue that rainfall enhancement is emerging as a viable contributor to addressing growing water security concerns in a warming climate. We specifically consider current progress and future directions for rainfall enhancement applications based on the experience of the United Arab Emirates (UAE) with its national decade-long operational cloud seeding program and its grant-based international research and development program.

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Water security, which we define as available, accessible and affordable access to fresh water supply, is one of the key areas impacted by climate change across multiple pathways. In response to water shortages exacerbated by population growth and climate change, an increasing number of countries have invested in weather modification technology over the past decade, specifically rainfall enhancement applications such as cloud seeding[1–3], to augment their water security approaches. Rainfall enhancement is a subset of weather modification that aims to augment natural rainfall amounts through airborne or ground-based interventions in the microphysical processes of specific cloud types[2].

## INTERNATIONAL EFFORTS AND CHALLENGES

When considering rainfall enhancement as part of an overall water security strategy, it is essential to be able to verify both efficiency and efficacy. Regarding efficacy, the most recent review[3] on global precipitation enhancement activities conducted by the World Meteorological Organization (WMO) Expert Team on Weather Modification, indicates that cloud seeding from aircraft platforms is generally more effective than other rainfall enhancement techniques, such as ground-based generators, customized rockets, and artillery shells. Operational aircraft-based cloud seeding programs spanning several countries record different ranges of average percentage increases[4] in both precipitation amount and cloud lifetime. However, it is important to note that none of the recent physically-based studies, such as the Seeded and Natural Orographic Wintertime Clouds: The Idaho Experiment (SNOWIE[5]) or the Wyoming Weather Modification Pilot Project (WWMPP[6,7]), suggest such large impact (10–30%). In the SNOWIE work, the few cases[8] that directly attributed precipitation to cloud seeding were in storms with little natural precipitation. In such instances, one might attribute a rather large percentage increase in precipitation to seeding, but only because the denominator (natural precipitation) is small. This results in a "scaling problem" discussed by Flossmann et al.[3]. Determining a basin-wide estimate of seeding impact requires integrating across storms for which there does not exist good physical estimates of seeding efficacy. This highlights why continued research is crucial, but also why it is critical to consider carefully how estimates are presented to policy-makers and the general scientific community.

The complex variability of cloud properties in both space and time makes it difficult to quantify accurately the impact of cloud seeding in lieu of naturally occurring rainfall. Partially similar to the methodology used for clinical trials, long-term randomized cloud seeding experiments are necessary to draw statistically significant comparative results between target (seeded) and control (unseeded) clouds. However, specific cloud conditions are transient and less accessible compared to human patients, making it particularly difficult to reproduce randomized cloud seeding experiments.

To overcome the limitations of field experiments, long-term statistical analyses have been carried out to evaluate seeding impacts using control-target regression[9] derived from historical rainfall records. However, such analyses rely exclusively on local rain gauge measurements that fail to capture potential changes in climate circulations that may influence local rainfall patterns, far beyond seeding effects. Therefore, investigating the effects of seeding by combining both physical and statistical analyses, which is considered the most systematic approach to evaluating cloud seeding experiments[3], is essential in further demonstrating the efficacy of seeding operations.

## CURRENT INSIGHTS REGARDING CLOUD SEEDING EFFICIENCY AND EFFICACY

In considering the potential for rainfall enhancement, there is perhaps no better place to look than the United Arab Emirates (UAE). The country's rapid growth over the course of the past few decades, compounded by rising temperatures, strained already limited renewable water resources—the mean annual rainfall in UAE is less than 80 mm per year[10]—creating a need for improved monitoring and capture of available rainfall. Since 2002, the UAE has implemented an operational aircraft-based cloud seeding program to augment its natural rainfall amounts.

The cloud seeding program is implemented by the UAE National Center of Meteorology (NCM), utilizing the conventional approach of igniting hygroscopic flares, composed of natural salts (primarily potassium chloride), from an aircraft at the base of convective clouds near the updraft core. The program operates

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[1]National Center of Meteorology, Abu Dhabi, United Arab Emirates. [2]Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates.
✉email: steven.griffiths@ku.ac.ae

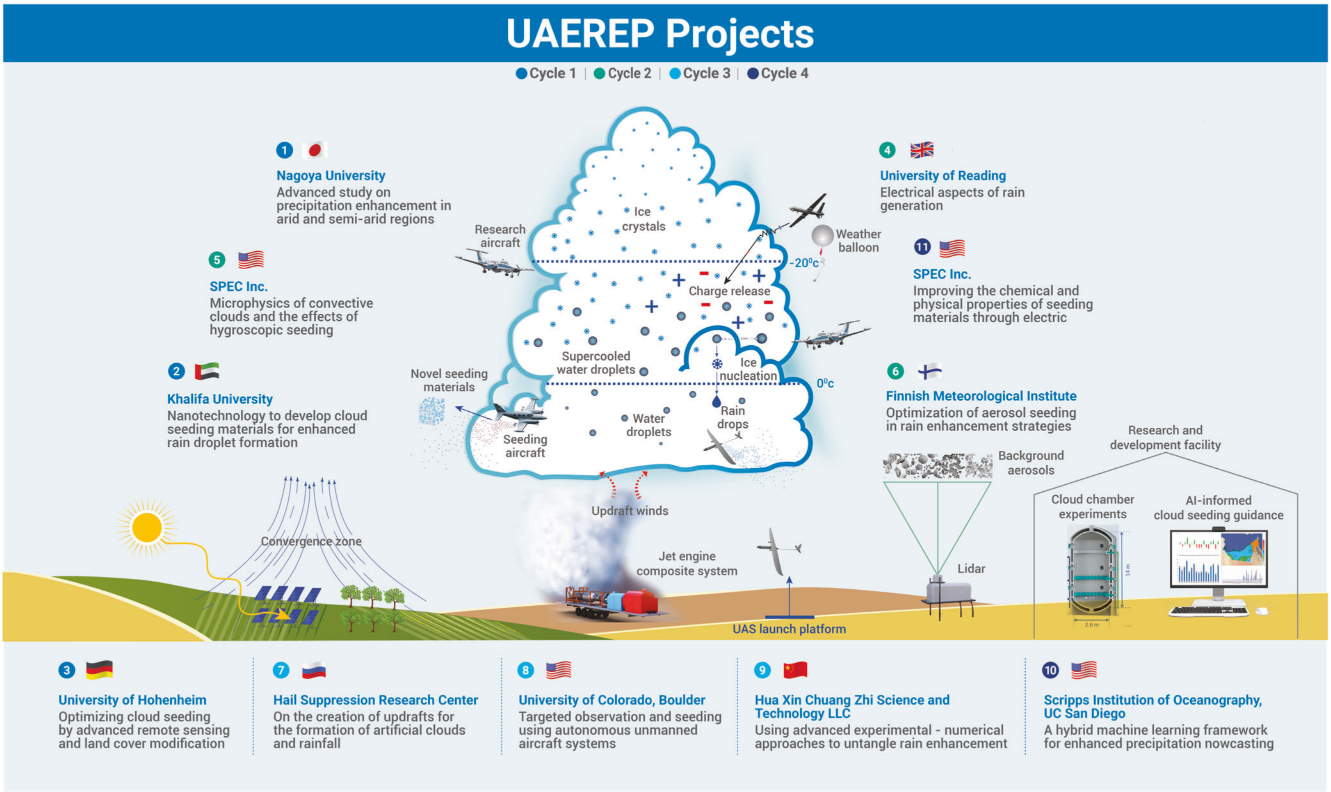

**Fig. 1 Conceptual representation of a mixed-phase cloud and planetary boundary layer.** The number labels are color-coded for each UAEREP award cycle (1–4). Each of the 11 UAEREP projects is presented in terms of country (flag), institution name and project title (top to bottom).

four Beechcraft King Air C90 aircraft based out of Al Ain Airport, situated near the foothills of the Hajar Mountains bordering Oman where frequent summertime convective cells[11] are targeted. Given the predictable diurnal cycle[12] of afternoon convection in this area and the isolated orographic cloud development, all clouds are seeded over this convective hotspot. The program also targets all mesoscale convective systems year-round across the country.

A recent study[4] reported the first attempt to evaluate objectively the long-term impacts of the UAE cloud seeding program. The study implemented a hybrid methodology combining both statistical and physical analyses of long-term rain gauge records from before (1981–2002) and after (2003–2019) the launch of the seeding program in addition to cloud properties from weather radar data. The radar-based physical analysis compared an archive of storm properties between unseeded (87) and seeded (65) storm samples, and showed consistent and systematic enhancements in storm properties within 15–25 min of seeding. These outcomes provide important insights into the long-term impacts of cloud seeding operations over the UAE and its contribution to water resources in similar arid and hyper-arid regions.

There are still too many multiscale and region-specific unknowns to report a specific percentage for seasonal (and annual) increases in precipitation from cloud seeding operations. The WMO peer review report[13] on global precipitation enhancement activities references increases in average seasonal precipitation ranging from 5 to 25%, reported by different programs. We use this range to provide a preliminary quantification of rainfall volumes resulting from cloud seeding over the UAE. In addition, despite the mentioned year-round targeting of all seedable clouds over the UAE, we assume a 50% target rate to estimate the volume of seeded rainfall. The UAE's historical annual average rainfall volume is ~6.7 billion cubic meters (BCM) based on the 83,600 km$^2$ surface area and 80 mm annual average rainfall depth. Applying the seeded rainfall increase range (5–25%) and the 50% target rate to the 6.7 BCM annual (natural) rainfall volume results in seeded rainfall volumes ranging from 168 to 838 million cubic meters (MCM) per year. We further reduce these volumes by roughly 50%[14], due to direct evaporation and soil moisture retention in the unsaturated zone, resulting in estimated harvestable water volumes ranging from 84 MCM to 419 MCM. Again, these are high-level estimates that require further research at local watershed scales to address the "scaling problem" mentioned in the introduction.

When it comes to the efficiency of cloud seeding, cost is a primary driver. In the UAE and other GCC countries, water tariffs are heavily subsidized and do not reflect actual production costs. However, the Dubai Electricity and Water Authority (DEWA) estimates a desalinated water production cost of \$0.31 per m$^3$ from its most advanced Hassyan Sea Water Reverse Osmosis Plant, which is less than the unit cost range of \$0.45 to \$1.9 per m$^3$ reported for different desalination methods and countries[15]. On the other hand, cloud seeding missions according to NCM cost up to \$8000 per flight hour, with 390 flights conducted in 2020, each with an average duration of 1 hour. When considering the determined range of harvestable rainfall volumes from seeding (84 MCM to 419 MCM), the unit cost of harvestable seeded rainfall can be estimated between \$0.01 to \$0.04 per m$^3$—up to 30 times less than the DEWA-based unit production cost of desalination (\$0.31 per m$^3$).

To harness the full potential of cloud seeding technology as a reliable and cost-effective source of renewable water, it is necessary to make parallel investments in rainwater harvesting and groundwater recharge systems, as well as efficient transmission systems. This is analogous to the critical challenges being tackled for solar energy storage and transmission. Further research is needed to conduct a holistic cost-benefit analysis that encompasses the multiple sectors involved in the full life cycle of cloud seeding technology.

It is therefore important to emphasize that rainfall enhancement technology should not be viewed as a substitute for other crucial components of water security, such as desalination and wastewater recycling and reuse. Instead, it should be considered a reliable complementary source of water, with specific applications in areas like targeted agriculture and managed aquifer recharge.

## THE PATH FORWARD FOR RAINFALL ENHANCEMENT

Despite its promise, aircraft-based cloud seeding technology has not emerged as a widely discussed approach to water security. In response, the UAE Research Program for Rain Enhancement Science (UAEREP[16]) was established under the NCM in 2015 to stimulate and promote scientific advancement and the development of new methodologies and technologies in the field. To this end, the UAEREP provides managed grant assistance to the international scientific community targeting innovative and interdisciplinary research on rainfall enhancement applications. A key priority of the program is to foster international collaboration in this field of research beyond conventional aircraft-based cloud seeding.

A total of 11 projects have been awarded to date, targeting multiscale processes, including land-atmosphere feedbacks, biogeo-engineering, aerosol-cloud-precipitation interactions, and mixed-phase cloud microphysics. The interdisciplinary nature of these projects leverages the latest advancements in material science and nanotechnology for the development of novel seeding materials[17], autonomous unmanned aerial systems[18] (UAS) for more robust and cost-effective seeding missions, smart sensors for in-cloud electrification[19], reverse-engineered thermal systems[20] to stimulate artificial updrafts and convection, and machine learning tools[21] for more efficient cloud forecasting and targeting systems. Figure 1 shows an infographic that consolidates the 11 projects funded by the UAEREP across 4 award cycles between 2016 and 2023.

In order for rainfall enhancement, and perhaps more specifically cloud seeding, to become a core component of national and regional water security strategies, we propose the following topics as being the most essential for further study:

(1) increasing targeted cloud quantity and precision (timing and location) of seeding missions,
(2) identifying optimal rainfall enhancement applications and requisite conditions (i.e., aerosol seeding, droplet electric charging or a hybrid approach) and
(3) deploying rainfall harvesting, water storage and transmission systems.

Importantly, these topics have relevance globally with outcomes including augmented rainfall in arid regions like the Middle East and mitigation of drought in Sub-Saharan Africa. In the long-term, a program such as UAEREP that integrates rainfall science with novel technologies and operational approaches could even achieve an overarching vision of using UAS driven by AI trained on synthetic data from physics-based weather models (running on supercomputers) to deploy state-of-the-art nanomaterials and other techniques (e.g., electric charge dispersion) to stimulate rainfall in any part of the world without exclusive reliance on highly trained staff and pilots in the process. This would have major impact in countries where skilled human capital is in short supply but water security challenges are abundant.

These research and technology developments require careful consideration of current and progressive ethical concerns. A recurring ethical concern regarding cloud seeding programs pertains to the issue of “extra-area” effects[3], that is, whether seeding can affect the weather beyond the targeted temporal or spatial range. Further quantitative studies are needed to resolve these issues, bearing in mind the uncertainties in assessing the impact of seeding in a designated target area. Also, the use of autonomous UAS for weather modification applications is a recently developing field and requires careful attention to legal and ethical considerations that are specific to different countries and areas of operation[22]. In addition, given the increased interest in developing new cloud seeding materials and strategies, high-resolution chemical fate and transport modeling is needed to investigate all toxicological pathways and residence times of these compounds. The basic pathways include deposition of seeding materials from the air and precipitation into soil and surface water, human and animal ingestion or uptake by biota, and deep infiltration into aquifers.

The presented technical and ethical assessments can only be addressed through international research collaborations and targeted investment in the field of rainfall enhancement. The UAE has been chosen to host the 2023 UN Climate Change Conference (28th Conference of the Parties, COP28), providing a significant opportunity for the region to showcase its commitment to combating climate change and promoting sustainable development. The UAE’s efforts in rainfall enhancement, combined with the country’s hosting of COP28, is an opportunity to advance the field of rainfall enhancement as a viable contributor to address the growing impacts of climate change on water and food security, regionally and globally.

## DATA AVAILABILITY

All data used in this comment are publicly available online.

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## AUTHOR CONTRIBUTIONS

S.G. and Y.W. conceived the ideas for this comment. Y.W. wrote this comment with editorial input from all authors.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

**Correspondence** and requests for materials should be addressed to Steve Griffiths.

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