Cloud Microphysical Properties Observations during the Saudi Arabia AeRosol-Cloud-Precipitation Enhancement Campaign (SARPEC)

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Abstract: Cloud microphysical properties

Introduction

Cloud seeding represents a form of weather modification has been shown to enhance precipitation in many statistical studies (e.g., (Tuftedal et al. 2022). Such studies analyze cloud seeding that involves introducing substances into clouds that serve as cloud condensation nuclei or ice nuclei, which alters the microphysical processes within clouds to stimulate precipitation. Since its inception in the 1940s (Schaefer 1968), cloud seeding has evolved from experimental research to operational programs implemented in various regions worldwide (Bruintjes 1999). Cloud seeding is of particularly in arid environments where water resources are limited.

The fundamental objective of cloud seeding is to increase precipitation by enhancing the efficiency of natural processes within clouds. Cloud seeding increases efficiency by introducing materials that accelerate the condensation or freezing processes. In many instances, particularly in arid regions, clouds may contain adequate moisture but lack efficient precipitation mechanisms, resulting in minimal rainfall. Furthermore, the precipitation efficiency can decrease over time in arid regions (Liu et al. 2020). In arid regions such as Saudi Arabia, two principal seeding methods are employed. Glaciogenic seeding that targets cold clouds with temperatures below freezing and operates on the principle of introducing ice nuclei to initiate the Bergeron-Findeisen process. The glaciogenic seeding uses aircraft to release silver iodide containing particles by burning flares. The second method, hygroscopic seeding targets warmer clouds with temperatures above freezing to enhance the collision-coalescence process. Hygroscopic seeding is particularly relevant in arid regions where many clouds have base temperatures above freezing. Hygroscopic seeding employs salt particles, calcium chloride, potassium nitrate, and specially formulated hygroscopic flares containing mixtures of salts.

The implementation of cloud seeding represents a significant scientific endeavor addressing critical water resource challenges. The technology aims to increase rainfall, augment water supplies, mitigate drought impacts, and support sustainable development. As scarcity concerns intensify, the research outcomes from weather modification programs is important to provide valuable insights for considerations in an overall water management strategy in arid environments. With an average annual rainfall of less than 100 mm in most regions and increasing water demands, the Kingdom of Saudi Arabia's has a long history in weather modification and cloud physics research that dates back to the 1970s. In 2006, the Kingdom of Saudi Arabia launched a comprehensive cloud physics research program in collaboration with international partners. The project used research aircraft and C-band radars to document aerosol, cloud and precipitation conditions. Radar analysis documented that along the south-west escarpment there are March-April and August seasonal precipitation peaks (Kucera et al. 2010). Additionally, feeder clouds were shown to be a valuable source of water for Saudi Arabia (Krauss et al. 2011). The Riyadh region of Saudi Arabia was shown to have below cloud base aerosol concentrations of approximately 600 cm^{-3}, which is higher than Mail, West Africa but lower than summer-time North Dakota, United States (Delene et al. 2011). However, one distinguishing aerosol character of Saudi Arabia is dust, which can affect the cloud microphysical properties. Wind lifted dust likely resulted in sufficiently different cloud properties during the 9 April 2009 "Brown Ice Layer" sampling where peak droplet concentrations increased (Figure 1) and peak mean droplet diameter decreased (19 μm to 14 μm,not shown) while peak liquid water content remain relatively constant (1.5-2.0 g m^{-3},not shown).

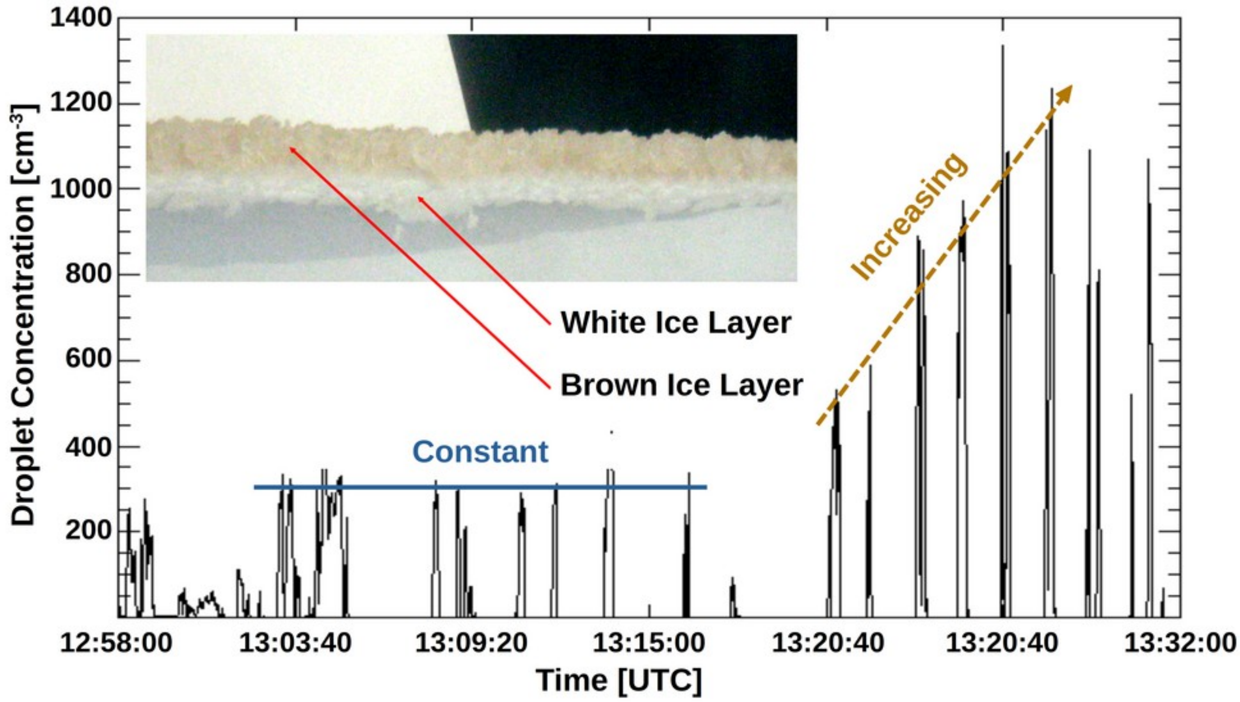

Figure 1: Time series (1 Hz) of cloud properties at 18,000 ft on the 9 April 2009 flight in Saudi Arabia. Droplet concentration are measured with a Forward Scattering Spectrometer Probe (FSSP). The blue, solid line denotes relatively constant peak cloud droplet concentrations during "White Ice Layer" sampling. The brown, dash line denotes increasing cloud droplet concentrations during "Brown Ice Layer" sampling. During the The picture insert shows the ice build up on the right wing of the King Air 200 Research Aircraft.

Despite many field projects, the detailed microphysical characteristic and precipitation formation process are not well understood for the highly variable regimes found in Saudi Arabia. There is a need to understand the complex interactions between dust aerosols and cloud microphysical processes. Additionally, the interactions between microphysical processes and dynamic feedback needs to be fully characterized. Hence, there are science gaps from previous campaigns and limitations to our knowledge. Hence, a new series of field projects, Saudi Arabia AeRosol-Cloud-Precipitation Enhancement Campaign (SARPEC), was conducting in 2023 and 2024 with the overarching goal of determine the effectiveness of current cloud seeding operations in the Kingdom and how can optimal results be obtained.

Objectives

The SARPEC field project objectives include building a contemporary cloud microphysical dataset from actively growing convective clouds, specifically those amenable to seeding. The dataset included both the southwest and central operational areas and observations in different seasons. The created dataset enables the establish of temperature and altitude levels where supercooled liquid water exists, the temperatures where ice first starts to form, and how the ice formation level changes with the cloud's life cycle. Detailed analysis of the dataset enables determination of the modes of precipitation development. Analyzing the cloud penetrations made at different levels above cloud base determines how liquid water content changes with decreasing temperature (increasing height). Such analyzes informs the scientific objectives of subsequent research flight campaigns using the new National Center for Meteorology King Air Research Aircraft (NCM KA360).

Data Set

Saudi Arabia's climate is characterized by predominantly hot and dry desert conditions with significant variations in the southwestern region (Hasanean and Almazroui 2015). The southwestern mountainous areas, including the Asir Mountains (Figure 2) and Jizan Province, experience a unique weather pattern influenced by the Indian Ocean monsoon system. The monsoon creates a distinct summer precipitation regime in late July and August when moist air masses from the Indian Ocean move northwestward and encounter the mountainous terrain. The orographic effect plays a crucial role as the Asir Mountains, with elevations exceeding 3,000 meters, form a significant barrier that forces moisture-laden air upward, triggering convective precipitation. The windward western slopes receive substantially higher rainfall (> 300 mm annually) due to this orographic lifting, making it the wettest region in the country. The leeward eastern slopes experience a pronounced rain shadow effect, transitioning rapidly to arid conditions. Monsoon-induced convective precipitation produces afternoon thunderstorms with intense but relatively short-lived rainfall events, sometimes leading to flash flooding. The summer-dominant precipitation pattern in the southwest region contrasts sharply with the rest of Saudi Arabia, where northern and central regions receive minimal rainfall primarily during winter months, eastern coastal areas experience occasional thunderstorms associated with winter frontal systems, and the Rub' al Khali in the southeast remains almost entirely dry throughout the year.

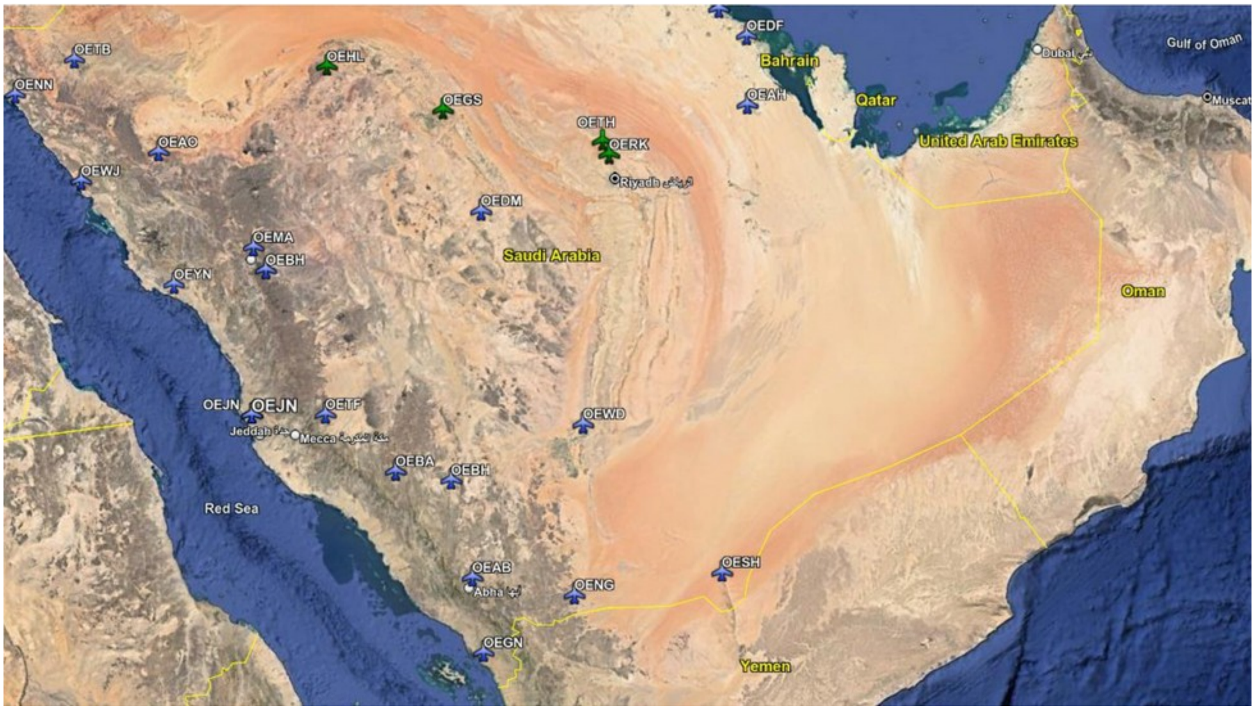

Figure 2: Image showing Saudi Arabia with surface geographical features. The national borders are given by solid yellow lines. The Citation Research Aircraft was based at the Rabigh Airport (OERB) for the Summer 2023 intensive operations period (IOP1) and at the Thumamah Airport (OETH) for the Fall 2023 IOP2 and Winter 2024 IOP3.

The central region of Saudi Arabia, known as Najd (Figure 2), is characterized by a vast plateau that gradually slopes eastward from the western highlands, with elevations ranging from 600 m to 1,500 m above mean seal level (AMSL). This heartland of the Arabian Peninsula features the dramatic Tuwaiq Escarpment, an 800 km long cliff formation that runs north-south, creating a natural boundary between different ecological zones. The Rub' al-Khali (Empty Quarter) is in the south and Wadi Hanifa is a major valley running through the Riyadh region that has historically provided vital water resources. The southwest region presents a striking contrast with the Asir Mountains, which creates Saudi Arabia’s highest elevations, with Jabal Sawda reaching approximately 3,000 meters. The south-west area is defined by the Great Escarpment, where the land drops sharply from the highlands toward the Red Sea coastal plain. Unlike much of Saudi Arabia, the southwestern highlands receive significant rainfall to support terraced hillsides, agricultural areas, and unique fog forests in the higher elevations. The south-west area was the focus of the Summer 2023 intensive operations period (IOP1).

Describe the citation research aircraft and instrumentation (e.g., Cloud Droplet Probe, Precipitation Imaging Probe, Cloud Imaging Probe) for measuring cloud microphysical properties (Figure 3).

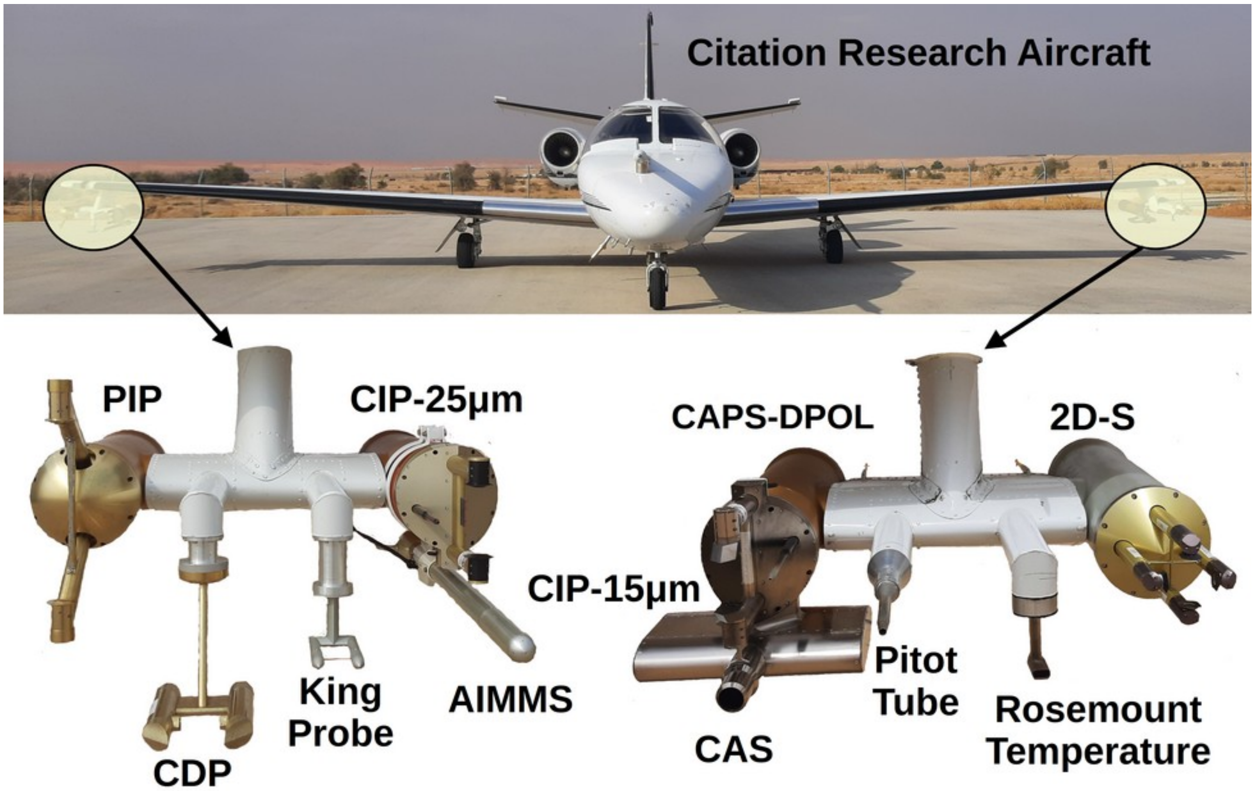

Figure 3: Images showing the Citation Research Aircraft used for Saudi Arabia AeRosol-Cloud-Precipitation Enhancement Campaign (SARPEC). Under the aircraft's left wing is a pylon housing the Two-dimensional Stereo Probe with 10 µm diodes, the Rosemount Temperature probe, a Pitot Tube, and the Cloud, Aerosol, and Precipitation Spectrometer with Depolarization (CAPS-DPOL). The CAPS-DPOL has a Cloud Imaging Probe with 15 µm diodes (CIP-15µm), a cloud Aerosol Spectrometer (CAS), and a pitot tube. Under the aircraft's right wing is a pylon housing a Cloud Imaging Probe with 25 µm diodes (CIP-25µm), an Aircraft Integrated Meteorological Measurements System (AIMMS), a King Probe, a Cloud Droplet Probe (CDP), and a Precipitation Imaging Probe with 200 um diodes (PIP).

Describe the flight campaigns (IOP1 over Southwest and IOP2/IOP3 over Central Saudi Arabia), including the number of research flights (IOP and flight number) and description of each flight. (Table 1).

Methodology

The Citation Research Aircraft conducts very effective micro-physical measurements of cloud and precipitation particles; hydrometeors ranging from small cloud droplets all the way up through hailstones can be recorded. Vertical wind, aerosol, temperature, and humidity profiles will also be recorded to fully document the sampled clouds as well as their environment. During the research deployment, clouds that meet the operational requirements of the seeding program will be selected for sampling. Such clouds may be organized in linear forms, isolated, or appear in clusters. Briefly restated, the clouds of interest for hygroscopic and glaciogenic seeding are those having updraft, and in the case of glaciogenic seeding, supercooled liquid water, and a lack of natural ice. Clouds without updrafts are no longer growing, and those containing significant ice have already produced it naturally, making seeding unnecessary.

Sampling of clouds in the southwest region of Saudi Arabia starts with sampling at the -10 °C level since conditions along the escarpment make sampling under cloud base impossible. Each pass begins at the prescribed altitude, but upon entering cloud the aircraft is flown at a constant attitude to avoid accumulation of ice on the underside of the aircraft, and to optimize the vertical wind measurement. Cloud passes may be conducted once, or several times depending on how fast the cloud is maturing. Each sampling level is followed by an ascent and turns out-of-cloud, and repeated until the top of the cloud is reached. Figure 3 illustrates the standard flight profile that will be used for sampling during the field program. Ideally, the -10 °C, -15 °C, -20 °C, and -25 °C levels will be sampled as the cloud matures. Sampling may not be conducted at all these levels initially since the cloud may not have matured sufficiently to extend to the colder temperatures. In this case sampling will continue at the upper two levels until the cloud system has matured to capture the cloud evolution. The Citation Research Aircraft has the performance to effectively conduct cloud sampling at all desired cloud levels.

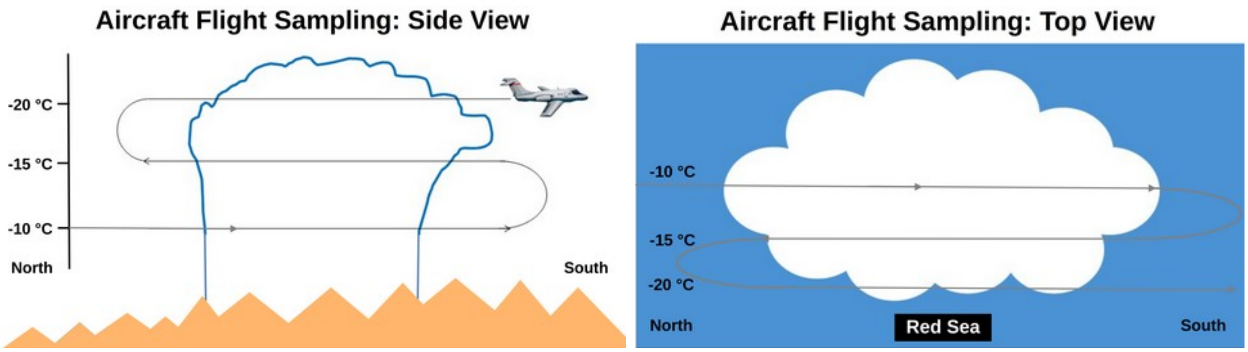

Figure 4: When a cloud suitable for sampling is identified the research aircraft will perform a series of pre-planned passes, initially out of cloud, and then in-cloud. This flight profile should be conducted in unseeded (natural) clouds, and with seeded clouds. The effects of seeding can thus be observed. In some instances it may be desirable for the research aircraft to penetrate the target cloud at or near seeding altitude prior to seeding, thus obtaining “natural” characteristics

Results

Particle size distribution plot (merged from all instruments) for an unseeded vs. seeded case (23/31 March or 03 April) that shows some broadening of the seeded cloud DSD. We will certainly point out caution in interpreting this as a "seeding effect" given the limited data, but the objective is to show them that we have measurements from both seeded and unseeded clouds.

Discussion

We can overlay effective radius vs. temperature for KSA curves (one for IOP1 "Southwest" and another for IOP2-3 "Central"). I expect something similar to the UAE curve - no extension beyond the 12-14 micron active coalescence zone (grey shade), which indicates good seeding candidates.

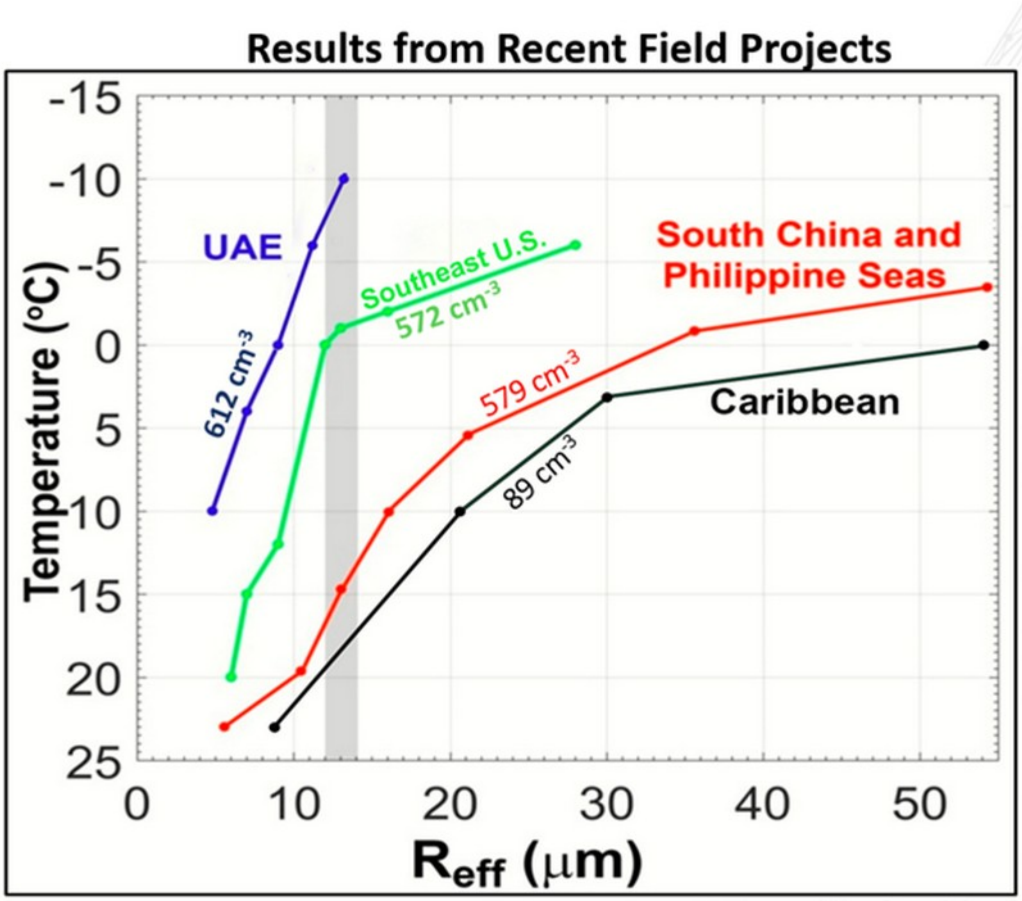

Figure 5: Illustration of how droplet size changes with height for different locations.

Droplet Size Distribution and Coalescence: Highlight the findings from IOP1 in the Southwest, where clouds exhibited significant variability in droplet size and concentration. Explain the importance of the lack of (or limited?) natural droplet coalescence, which makes clouds suitable for hygroscopic seeding.

Ice Formation and Mixed-Phase Clouds: Discuss the vertical distribution of supercooled liquid water and ice particles observed at altitudes of -10°C, -15°C, and -20°C. Explain how these properties are relevant for glaciogenic seeding.

Updrafts and Cloud Life Cycles: Analyze the role of updrafts in cloud growth and the implications for seeding during the early development phase of cumulus clouds.

Smaller Droplet Growth in Central Region: Present the key finding from IOP2 that clouds in the Central region had smaller increases in droplet size with altitude, indicating less coalescence.

Ice Particle Aggregation: Discuss observations related to ice crystal aggregation and secondary ice production (SIP) processes in Central Saudi Arabia. Connect this to the potential success of glaciogenic seeding in these clouds.

Comparison of Cloud Properties Between Regions: Compare cloud microphysical properties between the Southwest and Central regions, emphasizing differences in coalescence, ice formation, and cloud structure.

Implications for Glaciogenic and Hygroscopic Cloud Seeding

Hygroscopic Seeding Potential: Analyze how the cloud properties in Southwest Saudi Arabia (e.g., small initial droplet sizes and suppressed coalescence) support the use of hygroscopic seeding to promote raindrop formation.

Glaciogenic Seeding Potential: Discuss how the existence of supercooled liquid water and ice particle formation at different altitudes in both regions suggests favorable conditions for glaciogenic seeding.

Challenges with Seeding in Dust-Laden Environments: Address the impact of high background aerosol loadings (e.g., dust particles acting as cloud condensation nuclei) and how they might affect the efficiency of seeding operations.

Conclusion

Summary of Key Findings: Recap the cloud microphysical properties observed in both regions and their implications for cloud seeding.

Importance of Continued Research: Emphasize the importance of continuing research and data collection in order to optimize cloud seeding operations in Saudi Arabia, contributing to diversifying water resources in the Kingdom.

Future Work

Limitations of Current Data: Discuss challenges faced during data collection, such as air traffic control restrictions and limited cloud lifetime.

Need for Enhanced Modeling and Data Collection: emphasize the need to use the dataset in cloud-scale modeling to investigate seeding impacts, alongside addition measurements using the NCM KA 360

Acknowledgments

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