## MICROPHYSICS AND DYNAMICS OF CONVECTIVE CLOUDS AND THE EFFECTS OF HYGROSCOPIC SEEDING: SYNTHESIS OF AIRCRAFT MEASUREMENTS, POLARIMETRIC RADAR OBSERVATIONS AND MICROPHYSICAL MODELING

**Final Report**

**UAE Research Program for Rain Enhancement Science**

### Reporting Period

(PLEASE FILL IN THE INFORMATION BELOW)

<table>
<thead>
<tr>
<th>Reporting Period</th>
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<tr>
<td><strong>Start Date</strong></td>
<td>1 March 2017</td>
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<tr>
<td><strong>End Date</strong></td>
<td>1 September 2020</td>
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<tr>
<td><strong>Submittal Date</strong></td>
<td>1 November 2020</td>
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### Prime Institution Name

**Principal Investigator**

| Dr. R. Paul Lawson                           | SPEC Incorporated    |
**EXECUTIVE SUMMARY**

- **Summary of Scientific and Technical Progress vs. Plan:**

  The overall goal of our UAEREP project was to investigate the potential to artificially stimulate a natural secondary ice process (SIP) in cumulus clouds to enhance precipitation. In order to accomplish this goal, it was proposed to study the microphysics and dynamics of cumulus clouds in the U.S. and the UAE. The strategy is a three-prong approach including measurements from research aircraft, analysis of ground-based radar data and modeling studies. Accordingly, a SPEC Learjet Model 25 research aircraft was used in 2017 and collected data in cumulus clouds over the High Plains in the Western United States. A SPEC Learjet Model 35A research aircraft was flown to the UAE and collected data in cumulus clouds during August 2019. The field campaign in the UAE was initially scheduled to take place in 2018, but transfer of the Lear 25 research instrumentation to the Lear 35A and FAA certification was not complete, so the field project was rescheduled for August 2019. Radar data from the summer of 2016 was analyzed to determine the best location, time of year and time of day to study clouds in the UAE. Numerical simulations were conducted by Dr. Hugh Morrison, senior scientist at the National Center for Atmospheric Research (NCAR). The modeling results support the data collected with research aircraft and ground-based radar. We have placed the modeling code in the UAEREP/Khalifa University repository, and all of the research aircraft and radar analyses are being archived.

  Data collected in the U.S. and the UAE focused on cumulus congestus (CuCg) clouds, which were ascertained to be the most suitable for rain enhancement. Overall, except for the delay in execution of the field project in the UAE, all of the program goals were achieved in a timely manner.

  Analysis of the collected data indicate that CuCg clouds in the UAE typically have cloud base temperatures of about 10 °C, which does not produce sufficient depth of warm cloud to naturally generate a strong coalescence process. A strong coalescence process is required to produce supercooled large drops (SLDs) that may fracture upon freezing and produce several small ice particles. The small ice particles will collide with other SLDs, producing more small ice particles, inducing an avalanche process that rapidly glaciates the updraft and enhances rainfall.

  Since CuCg clouds in the UAE do not naturally produce significant quantities of SLDs, the question arises: Will seeding with an appropriate hygroscopic material generate cloud condensation nuclei (CCN) that will modify the drop size distribution (DSD) in a way that stimulates coalescence? If the coalescence process is enhanced to the extent that an adequate concentration of SLDs are produced, this can initiate a natural SIP that leads to rain enhancement. Data analyzed under this grant show that UAE CuCg clouds develop weak coalescence with SLDs in a very low concentration. If the clouds can be stimulated via hygroscopic seeding with the proper seeding material, there is the possibility that the coalescence process can be enhanced to produce SLDs in sufficient concentration to initiate the natural SIP and increase precipitation. This possibility cannot be fully evaluated without further research, including a series of tests with existing and new hygroscopic seeding materials.
SPEC carried out a test of a new seeding material that is coated with a layer of Titanium dioxide (TiO$_2$) using a nano-technology process. Results from tests with the TiO$_2$ seeding material are inconclusive, but suggest that the TiO$_2$ material may enhance the drop concentration in the 10 to 30 µm size range, which is a favored size region to enhance the coalescence process. Additional randomized cloud seeding trials with the Learjet research aircraft and a NCM seeding aircraft within the UAE will be required to provide data capable of answering this question. A final analysis of aircraft and radar data collected in the U.S. and UAE is included this report along with results of numerical modeling studies. Publications of the observations and modeling studies will appear in peer-reviewed journal articles in 2021.

SPEC is currently working with Prof. Hannele Korhonen’s group at the Finnish Meteorological Institute (FMI) to incorporate their studies of aerosol composition with our in situ cloud studies. FMI and SPEC did not collaborate on their original proposals, and the symbiosis of their efforts has only became recognizable after their respective UAEREPE projects. A comprehensive analysis of aerosol composition incorporated with in situ cloud measurements will provide a better understanding of how cloud condensation nuclei (CCN) and ice nucleating particles (INP) influence precipitation, and how best to modify clouds in the UAE. Recent collaboration with FMI has only progressed to the discussion stage, which has been focused on how to obtain additional funding in order for both institutions to proceed.
SCIENTIFIC AND TECHNICAL PROCESS

Overall Project:

All of the Milestones listed in the Gantt chart (Figure 1) that were accepted from the last annual report and 30-month site review have been achieved, except for final peer-reviewed publications. Several publications describing the modeling work have already appeared in peer-reviewed journals. These publications focus on improvements to microphysical models and do not yet incorporate data from the field campaigns, which is a work in progress and will be included in future publications. It was agreed at the 30-month site review that work on publications would continue for 6 to 12 months after the official close of the contract. The Gantt chart is annotated in red text within each Milestone box describing the status of the Milestone.
<table>
<thead>
<tr>
<th>Number</th>
<th>Task</th>
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<tbody>
<tr>
<td>1</td>
<td>Calibrate Learjet instruments and prepare logistics for first field season in the U.S.</td>
<td>3/1/17</td>
<td>9/1/20</td>
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<tr>
<td>2</td>
<td><strong>Milestone:</strong> Learjet and logistics finalized for first field season in the U.S.</td>
<td>6/1/17</td>
<td>6/1/17</td>
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<tr>
<td>3</td>
<td><strong>Milestone:</strong> Learjet and radar data during first field season in the U.S.</td>
<td>6/1/17</td>
<td>9/30/17</td>
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<td>4</td>
<td><strong>Milestone/Deliverable:</strong> 6-month progress report submitted.</td>
<td>9/1/17</td>
<td>9/1/17</td>
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<td>5</td>
<td>Preliminary Analysis of Learjet and radar data from first field season in U.S.</td>
<td>9/30/17</td>
<td>12/31/17</td>
</tr>
<tr>
<td>6</td>
<td>Modifications added to Norwegian-Grabowski model to run in WRF.</td>
<td>3/1/17</td>
<td>12/31/17</td>
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<tr>
<td>7</td>
<td><strong>Milestone/Deliverable:</strong> Preliminary analysis of Learjet and radar data. Determination of cloud parameters required for investigation in UAE. M-G model modified. Annual report submitted to NCM.</td>
<td>1/1/18</td>
<td>1/1/18</td>
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<td>8</td>
<td><strong>Milestone/Deliverable:</strong> Preliminary Results from Learjet flights in the U.S. presented at the AMS Conference on Weather Modification.</td>
<td>1/7/18</td>
<td>1/11/18</td>
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<td>9</td>
<td>Preliminary Results from Learjet flights in the U.S. presented at the UAEREP Workshop.</td>
<td>1/14/18</td>
<td>1/18/18</td>
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<tr>
<td>10</td>
<td>Calibrate Learjet Instruments, install ADS-B and TCAS 7.2 avionics.</td>
<td>5/1/17</td>
<td>8/15/18</td>
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<tr>
<td>11</td>
<td>Train Khalifa grad student in cloud physics. <em>(Capacity Building and Knowledge Transfer)</em>.</td>
<td>2/1/18</td>
<td>11/15/18</td>
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<tr>
<td>12</td>
<td>Coordinate with NCM and GCCA ACC to conduct second field season in UAE in 2019.</td>
<td>4/1/18</td>
<td>5/5/18</td>
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<tr>
<td>13</td>
<td><strong>Milestone/Deliverable:</strong> Year 2 annual report submitted to NCM.</td>
<td>9/1/18</td>
<td>9/1/18</td>
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<tr>
<td>14</td>
<td>Ferry Learjet to UAE. Reinstall instruments and test fly.</td>
<td>7/31/19</td>
<td>8/3/19</td>
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<tr>
<td>15</td>
<td>Coordinate with NCM and conduct second field season in UAE. Incorporate tests of nano-material into flight operations. Train Khalifa grad student in field operations <em>(Capacity Building and Knowledge Transfer)</em>.</td>
<td>7/23/19</td>
<td>8/31/19</td>
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<tr>
<td>16</td>
<td>Ferry Learjet from UAE.</td>
<td>8/31/19</td>
<td>8/31/19</td>
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<tr>
<td>17</td>
<td><strong>Milestone/Deliverable:</strong> UAE field project and nano-material seeding tests complete. Invoice for 50% of 3rd year funding submitted and paid.</td>
<td>9/1/19</td>
<td>9/1/19</td>
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<tr>
<td>18</td>
<td>Conduct 3-month site visit from NCM personnel.</td>
<td>10/16/19</td>
<td>11/16/19</td>
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<td>19</td>
<td><strong>Milestone/Deliverable:</strong> Respond to issues raised in NCM evaluation of 30-month site visit.</td>
<td>11/10/19</td>
<td>11/10/19</td>
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<tr>
<td>20</td>
<td>Analyze Learjet and radar data from 2019 field season in the UAE. Modifications added to M-G model to run in 3-D.</td>
<td>9/1/19</td>
<td>9/1/20</td>
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<tr>
<td>21</td>
<td>Prepare and submit 3rd Annual Report to NCM.</td>
<td>9/1/19</td>
<td>12/31/19</td>
</tr>
<tr>
<td>22</td>
<td>Participate in UAEREP 4th International Rain Enhancement Forum in Abu Dhabi.</td>
<td>1/19/20</td>
<td>1/21/20</td>
</tr>
<tr>
<td>23</td>
<td>Incorporation of Learjet and radar analyses into numerical model. Khalifa grad student trained in application of model <em>(Capacity Building and Knowledge Transfer)</em>. Analysis to determine potential for rain enhancement in the UAE.</td>
<td>3/1/20</td>
<td>9/1/20</td>
</tr>
<tr>
<td>24</td>
<td><strong>Milestone/Deliverable:</strong> Final Report on scientific results and potential for rain enhancement submitted to NCM. Publication of results in peer-reviewed journals.</td>
<td>9/1/20</td>
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Figure 1. Gantt chart showing accomplishments to date.
Individual Tasks/Projects:

Analysis of Microphysical Data Collected with the SPEC Learjets
Dr. Paul Lawson¹, Dr. Roelof Bruintjes², Dr. Sarah Woods¹ and Dr. Colin Gurganus²

¹ SPEC Incorporated, Boulder, Colorado, USA
² Advanced Radar Corporation, Boulder, Colorado, USA

1. Preparation of Learjet 35A for Deployment to UAE in 2019

The Learjet 35A that was purchased by SPEC for the UAEREP project was converted to a research aircraft by installing and gaining FAA approval for a suite of microphysical instruments that were transferred from the Lear 25. In addition, in order to overfly countries in the European Union, the aircraft was required to undergo extensive upgrades to it avionics, including addition of two Garmin 750 primary function displays and ADS-B in and out. Figures 2 - 5 show photographs of the Learjet with external sensors, the Learjet inflight over the UAE, interior instrument racks installed in the cabin and new avionics in the cockpit.

Figure 2. Learjet 35A that was deployed to the UAE for the field project in 2019.

Figure 3. Photograph of the SPEC Learjet in flight over the UAE in August 2019
Figure 4. External sensors and instrument racks installed in the cabin of the Learjet 35A.

Figure 5. Photograph showing Lear 35A cockpit with installation of dual Garmin 750 glass displays.
2. Learjet studies in the U.S. in 2017 and in the UAE in 2019

The SPEC model 25 Learjet collected data in CuCg clouds in Colorado, Wyoming, Texas and Nebraska during the summer of 2017. Figure 6 shows flight tracks of the Learjet, along with cloud base temperatures and droplet concentrations. The 2017 research flights showed that clouds over the High Plains were mostly continental in nature with average cloud base drop concentrations ranging from 413 to 827 cm$^3$, and temperatures ranging from $-14^\circ C$ to $+14^\circ C$. None of these clouds developed a strong coalescence process that produced SLDs in sufficient concentrations to generate a SIP.

The SPEC model 35A Learjet collected data in CuCg clouds in the UAE during August 2019. Figure 7 shows flight tracts for the eleven missions conducted in the UAE. The flights all originated from Al Ain airport and were focused on the lee side (west) of the Al Hajar mountains. As shown in the “first echo” study in Figure 8a, the foothill region of the Al Hajar range is the preferred location for the initiation of convection. Figure 8b shows histograms of the monthly frequency of first echoes and the time of day of first echoes. The histograms indicate that August is a preferred month and that first echoes typically occur from about 1100 to 1300 UTC.

Figure 6. Learjet model 25 flight tracks from the 2017 UAEREP campaign in the United States.
**Figure 9** shows flight tracks, cloud base temperatures and DSD concentrations for four flights that focused on developing CuCg. **Figure 10** shows skew-T soundings for the four flights. A predominate feature on all of the soundings is a stable layer that occurs between about 500 and 300 mb. The stable layer provides a cap to CuCg convection that limits cloud top temperatures to about –12°C to –20°C. Once the stable layer is broken, generally due to thermal buoyancy, cloud tops may, or may not, grow to colder levels and contribute to the production of larger convective systems. The four focus flights are the subject of case studies found in Appendix B. Highlights from investigations of the four flights are presented in the body of this report.

![Flight Tracks](image)

**Figure 7.** Learjet model 35A flight tracks from the 2019 UAEREP campaign in the UAE.
Figure 8a. First radar echoes from June – November 2016 in the UAE.

Figure 8b. Number of radar detectable storms as a function of date (left panel) and time of day (right panel).
Figure 9. Flight tracks from four flights where CuCg were studied in the UAE showing date, number concentration of drops measured about 300 m above cloud base and temperature at cloud base.
Figure 10. Skew-T soundings at Abu Dhabi airport (OMAA) taken at 12Z on the flight days and dates shown in Figure 9.

3. Instrumentation and Measurement Methodology

The Learjet was equipped with a suite of optical cloud probes and air motion measurement systems, including a wing-mounted passive cavity aerosol spectrometer probe (PCASP), a Fast Forward Scattering Spectrometer Probe (FFSSP), a Fast Cloud Droplet Probe (FCDP), a High Volume Precipitation Probe (HVPS), a 2D-S probe and a Hawkeye probe. Here we designate the standalone 2D-S measurements as 2D10, which are the H-channel of the 2D-S probe unless specified otherwise. The Hawkeye probe incorporates an FCDP, a 2D-S with 10-µm and 50-µm channels, designated as Hawk2D10 and 2DS0, and a Cloud Particle Imager (CPI).
The FFSSP is used for all in-cloud measurements on the Learjet, mainly due to its legacy and understanding of its performance characteristics. The FCDP has improved optics, but a complete understanding of its performance is a work in progress. The FCDP instruments are more sensitive to smaller particles (< ~ 6 μm), and the FCDP is used for subcloud aerosol measurements.

Particle size distributions from up to four optical instruments (FFSSP or FCDP, 2D10, 2D50 and HVPS) are shown in several figures in this document. In order to compute bulk properties, such as total particle concentration (Conc), liquid water content (LWC), ice water content (IWC), effective particle radius (Reff) and effective radar reflectivity (Z) over the entire size range, appropriate “breakpoints” are manually chosen and shown on the figures as colored dotted lines. The “breakpoints” are where the measurements from one probe end and the probe with the next larger size range begins. This enables the generation of a “Composite” particle size distribution (PSD), or drop size distribution (SDS) if the measurements are in warm cloud.

The effective particle radius is computed using two methods: Reff is computed by assuming the particles are spherical (based on their maximum dimension) and divides the third moment (radius cubed) by the second moment (radius squared). This calculation is most applicable for measurements that are composed of all water drops. Reff is computed from dividing particle mass, using the formula from Baker and Lawson (2006), by the projected area of the particle. This calculation is most applicable for measurements that are composed of all ice particles. LWC is calculated assuming the entire size distribution is composed of spherical water drops. IWC is computed assuming the entire size distribution is ice using the mass calculation from Baker and Lawson (2006). Liquid and ice size distributions in a mixed-phase region of cloud are determined by dividing the composite PSD into liquid and ice portions using CPI and 2D10 particle images (see Lawson et al. 2015).

4. Aerosol Measurements

Due to large portions of desert in the interior of the UAE and its proximity to seas both east and west of the country, the UAE boundary (mixing) layer can experience high aerosol loading. A passive cavity aerosol spectrometer probe (PCASP) that measures aerosols in the size range from 0.1 to 3 μm was not installed on the Learjet in 2017, but was installed for the field campaign in the UAE in 2019. The fast cloud droplet probe (FCDP), which sizes particles from 2 to 50 μm and 2D-5 probe that images particles from 10 to 1,280 μm are also capable of measuring larger aerosols. As shown in the examples in Figure 11, the sizes of aerosols measured just below cloud base near Amarillo, Texas in 2017 extend out to about 10 μm (Figure 11a), while aerosols in the mixing layer over the UAE during the 2019 campaign extend past 100 μm (Figure 11b).

Figure 12 shows CPI images of aerosol particles that were typically observed in the subcloud mixing layer during all four of the CuCg flights. The irregular-shaped images of aerosols are often interspersed with spherical images that could be deliquesced aerosols or evaporating water drops from wispy scud clouds. The large rod-like image appears to be botanical material, but this cannot be verified. Aerosol composition was not analyzed during either the 2017 or 2019 campaigns. However, data collected in 2005 by the NCAR King Air 200. As shown in Figure 13, the particles are mostly dust (Silicate mineral) aggregated with salt (NaCl) or coated with sulfate (CaSO₄) (Semeniuk et al. 2014). These particles are highly hygroscopic, supporting the growth of larger drops near cloud base (Semeniuk et al. 2014).
Figure 11. Aerosol size distributions from a) FCDP and 2D10 measured below cloud base at Amarillo, TX on 31 July 2017, and b) PCASP, FCDP and 2D10 measured below cloud base in the UAE on 12 August 2019.

Wehbe et al. (2020) analyzed vertical profiles of PCASP total (0.12–3 μm) and coarse mode (0.5–3 μm) number concentrations on 12 and 19 August 2019. During the descent on 12 August, the total concentrations increased from around 1000 cc⁻¹ to 2000 cc⁻¹ within the boundary layer up to 5 k ft, and drops again to 1000 cc⁻¹ at 10 k ft. Similar concentration gradient variability was evident between 10 k ft and 20 k ft. The variation of concentration-altitude gradients suggests the presence of at least four distinct dust layers, which is in general agreement with ground-based Lidar observations from Filiolglou et al. (2020) over Al Dhaid. Fililiglou et al. (2020) report seasonal variations in the number of dust layers with up to five separate layers (up to 20,000 ft) observed during August 2018. The dust layer stratification is imposed by gravitational waves produced from the sea breeze-mountain overpasses during the afternoon period and by multiple temperature inversions frequently observed during the summer months Weston et al. (2020).

In both flight cases (12 and 19 August), the coarse mode aerosol number concentrations increase with altitude to peaks of approximately 80 and 20 cc⁻¹ at cloud bases (~12,000 ft) during 12 August and 19 August, respectively. This is explained by the aggregation of fine mode particles at high relative humidity, particularly over the southwest (19 August), where local pollution of predominantly sulfate composition is significant Semeniuk et al. (2015). The fraction of course mode aerosols near cloud base is less during the 12 August mission (~10%) compared to the mission on 19 August (~20%), which is explained by a higher fine-mode loading of desert aerosols (Wehbe et al. 2020).
Figure 12. Examples of CPI images of sub-cloud aerosol particles observed in the UAE during the Learjet mission on 12 August 2019.
Figure 13. Bright-field images of typical individual aerosol particles: (a) Silicate/gypsum aggregate particle; (b) NaCl single grain; (c) Silicate/NaCl aggregate particle; (d) Silicate/NaCl aggregate particle with additional gypsum and mixed cation sulfate (MCS) components (from Semeniuk et al. 2014).

5. Cloud Microphysics – Warm Cloud Region

The Learjet routinely sampled about 300 m above cloud base elevation to obtain microphysical and dynamic characteristics of the updraft (typically referred to as “cloud base penetrations”). This is
the location where CCN will have activated in the updraft and grown into drops that are large enough to detect with optical probes. This is a very important starting point for development of the updraft and cloud hydrometeor size distributions. **Figure 10** shows a time series of cloud base LWC and updraft characteristics for cloud base penetrations from the four days when CuCg were investigated over the UAE. The means of the measurements (black trace) shows that the updraft typically ranged between 0 and 2 m s⁻¹ and LWC ranged between 0 and 0.45 g m⁻³.

![Graph showing updraft velocity and Nevzorov liquid water content (LWC) measured](image)

**Figure 14.** Time series of a) updraft velocity and b) Nevzorov liquid water content (LWC) measured about 300 m above cloud base for the four days that the Learjet investigated CuCg in the UAE. Thicker black traces are means of the measurements.

**Figure 15** shows a comparison of average DSDs from cloud base penetrations conducted over the High Plains and in the UAE. The CuCg clouds investigated in the UAE had cloud base temperatures ranging from 9 to 11 °C and drop concentrations that ranged from 441 to 762 cm⁻³. However, the cloud base DSDs in the UAE are much broader, extending out to 100 µm compared with 40 µm in the High-Plains clouds. The cloud-base DSDs in **Figure 15** all have relatively high total drop concentration, which has been suggested by some studies to inhibit coalescence (e.g., Squires 1956, 1958). In his review of CCN properties, Hudson (1993) suggests that cloud base DSD concentrations exceeding about 200 cm⁻³ are thought to be an upper limit for the coalescence process. The clouds studied in the U.S. did not produce coalescence, except in one case, the mission on 31 July 2017 near Amarillo, Texas (AMA), where a very weak coalescence process was observed in a CuCg with a base temperature of + 14 °C. CuCg in the UAE also produced very weak coalescence, with very rare millimeter drops.
Figure 15. Drop size distributions measured about 300 m above cloud base during a) 2017 in the U.S., and b) in the UAE in 2019. Average total drop concentrations and cloud base temperatures are shown for each cloud pass.

In stark contrast to CuCg over the High Plains and in the UAE, a very strong coalescence process was observed in the Caribbean during the Ice in Clouds – Tropical (ICE-T) experiment. Figure 16 shows a comparison of average cloud base DSDs from the Caribbean, UAE, and the High Plains. The two distinguishing features between UAE and Caribbean cloud base DSDs are the higher concentration of
drops in the 10 to 30 µm size range and the considerably warmer cloud base temperature in the Caribbean (+ 22 °C). The greater depth of warm cloud in the Caribbean compared with UAE clouds, about 6,000 ft (1,830 m), is an obvious advantage for developing strong coalescence in Caribbean clouds. However, the lack of drops in UAE clouds in the size range indicated by the gray shaded area in Figure 16 is also significant. This is because the collision efficiencies of 60 µm drops with drops in the size range 30 µm < D < 10 µm are much lower than drops within the size range shown by the gray area in Figure 16. For example, Pinsky et al. (2001) show that the collision efficiency for a 60-µm diameter collector drop and a 10-µm collected drop is 3%, while the collision efficiency for a 60-µm diameter collector drop and a 25-µm collected drop is 46%, which is 15 times greater. The small drops tend to follow streamlines and flow around the larger collector drop. This is a possible explanation for the high coalescence in maritime (i.e., Caribbean) clouds, where the concentration of drops in the 15 to 30 µm size range are 1 to 2 orders of magnitude higher than any of the other locations.

![Cloud Base Drop Size Distributions](image)

**Figure 16.** Average drop size distributions and cloud base temperatures measured about 300 m above cloud base in the Caribbean, High Plains in Colorado, Amarillo, Texas and UAE. The gray area highlights a size region from about 10 to 30 µm where the drop concentration is significantly higher in the Caribbean.

Typically, broad DSDs measured within a few hundreds of meters above cloud base, such as observed in the UAE and the Caribbean, are conducive to supporting coalescence higher in an updraft (Johnson 1982; Jensen and Nugent 2017). Even though the cloud base DSDs in the UAE were as broad as CuCg clouds in the Caribbean, unlike UAE CuCg clouds, the Caribbean clouds produced strong coalescence and a vigorous warm-rain process. This is illustrated in Figure 17, which shows DSDs in all-liquid portions of clouds at – 5 °C from the High Plains, the UAE and the Caribbean, along with commensurate example 2D10 images.
Figure 17. (top) Drop size distributions (DSDs) in all-liquid cloud regions at about $-5\,^\circ C$ that correspond to the cloud base DSDs shown in Figure 16. (bottom) Example 2D10 images corresponding to the DSDs shown above.
Drizzle drops with diameters of about 200 to 500 \( \mu \text{m} \) were often observed in remnants of old cloud near and slightly above the bases of growing CuCg in the UAE. However, the drizzle drops observed within \(~100\) m above cloud base are unlikely to have been formed from CCN passing through cloud base, and are more likely to have been entrained from old decaying cloud. Using the enhanced condensational growth equation for ultra-giant CCN (Jensen and Nugent 2017), it would require more than ten minutes for an ultra-giant CCN to grow via condensation to 0.5 mm diameter in a 3 m s\(^{-1}\) updraft. However, it takes less than two minutes for the drops to reach the observation level 300 m above cloud base. Furthermore, drops with 0.5 mm diameter have a terminal velocity of about 2 m s\(^{-1}\), which means that it would be unlikely that they would be transported aloft in typical 1 to 2 m s\(^{-1}\) updrafts at cloud base in UAE CuCg. Due to the low concentration of these drizzle drops (\(\sim1\) m\(^{-3}\)) with a terminal velocity less than the mean updraft velocity near cloud base, the drops do not contribute to enhancing the coalescence process. The coalescence process is more likely to be advanced by drops that are 50 – 60 \(\mu\)m in size observed at cloud base in concentrations of 1 cm\(^{-3}\), about one-million times the concentration of the drizzle drops. Since isolated drizzle drops were sometimes observed in weak updrafts near cloud base, these regions were eliminated from the analyses.

6. Cloud Microphysics – Mixed-Phase Cloud Region

The Learjet was limited to 23,000 ft during the August 2019 campaign due to restrictions from UAE Air Traffic Control (ATC). This altitude corresponds to approximately the –10 to –12 \(^{\circ}\)C elevation in the UAE in August. As a result, there are no cloud data colder than about –12 \(^{\circ}\)C available from the UAEREP flights in August 2019. The temperature of the formation of “first ice” in UAE turrets is difficult to quantify for several reasons. The temperature at cloud top, which is the coldest portion of the cloud, must be known since ice nucleation is a strong function of temperature (Pruppacher and Klett 1997). Cloud top temperature often could not be measured in 2019 because of the ATC altitude restriction, and instead, was estimated from video taken by the Learjet forward-looking camera. The video was also used to eliminate turrets that could be contaminated by ice particles from higher, neighboring clouds.

There are penetrations of clouds as cold as –12 \(^{\circ}\)C that are free of ice and cloud penetrations at –6 \(^{\circ}\)C that contain large quantities of ice. This is demonstrated in Figure 18, which shows PSDs and examples of images from cloud penetrations at –6 \(^{\circ}\)C and –12 \(^{\circ}\)C on 12 August. The updrafts in UAE CuCg appear to be a series of thermal “bubbles” that sequentially rise, entrain dry air and dissipate (Scorer and Ludlam 1953; Blyth et al. 1988, 2005; Moser and Lasher-Trapp 2017, 2018). The bubbles rotate in a way that downdrafts develop at the edges (Blyth et al. 1988; Moser and Lasher-Trapp 2017, 2018). This is illustrated in a simulation found in Moser and Lasher-Trapp (2017) and reproduced in Figure 19. Generally, ice is observed in UAE CuCg clouds in these downdrafts at the edges of the updrafts. Thus, ice is often transported down from colder temperatures and entrained into the updraft via turbulent transport. As a result, it was necessary to measure or estimate cloud top temperature in order to determine the coldest temperature at which ice could have formed in an individual turret.
Figure 18. Examples of a) particle size distributions, b) CPI and c) 2D10 images sampled in a mixed-phase cloud at $-6.0 \, ^\circ C$ and d) particle size distributions, e) CPI, f) 2D10 and g) 2D50 images sampled in an all-liquid cloud at $-12.0 \, ^\circ C$ on 12 August 2019.
As shown in Figure 10, a stable layer between about – 5 °C and – 15 °C often caps convection in UAE clouds. The stable layer is typically associated with drying of the environment, which contributes to evaporation of water drops in ascending bubbles, eventually leading to negative buoyancy and dissipation of the updraft. Contrasting examples of this occurred when the Learjet penetrated turrets at – 5.3 °C on 18 August and at – 12.4 °C on 12 August. Figure 20 shows cloud photos, thermal profiles, LWC and updraft velocities measured in the two turrets. Figure 20a shows an example of the cloud penetration at – 5.3 °C with a ~3 °C decrease in temperature (negative buoyancy) and 8 m s⁻¹ downdraft. Note that the dew point temperature outside of cloud is ~ 38 °C, which will lead to significant evaporation in cloud and cooling due to dry-air entrainment (Cooper and Lawson 1984). In contrast the cloud penetration at ~ 12.4 °C in Figure 20b contains a 17 m s⁻¹ updraft and about 0.5 °C positive buoyancy at the peak of the updraft. The dew point temperature outside of cloud in this case is about ~ 20 °C and LWC is twice the value shown in Figure 20a. Note that in both cloud penetrations the temperature sensor may have been affected by sensor wetting, causing a decrease in temperature of 1 to 2 °C (Lawson and Cooper 1990). Even if this offset is considered, the maximum negative buoyancy in Figure 20a is still about – 1 °C and the positive buoyancy in Figure 20b is about +2.5 °C. The comparison in Figures 20a, b strongly suggests that negative buoyancy generated by entrainment of very dry air at the level of a cloud-top stable layer will not only limit vertical development, but can also aid in the generation of strong downdrafts.
Figure 20. a) Photo and b) time series of updraft velocity, liquid water content (LWC) from the hot-wire probe, temperature (T) and dew point temperature (T_d) measured in turret with negative buoyancy and an 8 m s⁻¹ downdraft sampled at – 5.3 °C; and c) photo and b) time series measured in turret with positive buoyancy and 18 m s⁻¹ updraft sampled at – 12.4 °C. Pileus in c) indicates strong updraft and red X’s show locations of cloud penetrations by the Learjet.

7. Seeding with NaCl-TiO₂

On 26 August 2019 the Learjet measured the size distribution of a new hygroscopic seeding material composed of NaCl salt particles enclosed in a TiO₂ shell. The new seeding material (TiO₂-NaCl) was developed under the UAEREP program using nano-technology (Zou et al. 2019). The nano-particles were released in clear air by an NCM King Air and the resulting plume was sampled by the Learjet (Figure 21). When released in an updraft at cloud base, the flares dispense TiO₂-NaCl hygroscopic seeding material in the 0.5 to 5 µm size range that may be appropriate to stimulate coalescence. However, the nucleating properties of the ICE-70, NCM and NaCl-TiO₂ seeding materials have not been sufficiently tested to determine if any of them are capable of stimulating coalescence in CuCg. It is recommended that a thorough study of all of these seeding materials in a cloud chamber and in CuCg clouds using seeding and research aircraft be conducted.

SPEC conducted a flight test in conjunction with the West Texas Weather Modification Association (WTWMA) on 1 September 2020. The NaCl-TiO₂ nano-material was released in clear air by the WTWMA seeding aircraft and penetrated by the SPEC Learjet (Figure 22). The size distribution of
the seeding material was similar to that observed in the UAE. However, the single-engine Comanche aircraft was not capable of climbing to cloud base to release the seeding material on this day, and the clouds were not CuCg that are suitable for the study, so no further seeding and cloud penetrations were conducted. Subsequently, the severe drought in West Texas precluded any possibility of finding suitable clouds and further studies are postponed until the spring of 2021. At that time, the seeding aircraft will release the NaCl-TiO₂ seeding material in updrafts at the base of CuCg clouds and the Learjet will make subsequent penetrations about 1,000 ft above cloud base to measure the DSD. This will provide a preliminary assessment of the effectiveness of the nano-material. More extensive tests need to be conducted to determine its effectiveness in enhancing the coalescence process.

**Figure 21.** A: Time series of FCDP measurements showing spikes when the Learjet intersected the nano-flares seeding plume in the UAE, and B: PCASP and FCDP PSD measurements in the seeding plume.

**Figure 22.** a) SPEC Learjet at the San Angelo, Texas airport, b) WTWMA single-engine Comanche seeding aircraft, c) photo from Learjet forward video 1-s prior to entering NaCl-TiO₂ plume, and d) NaCl-TiO₂ plume 30 ms prior to plume penetration.
8. Summary of Aircraft Studies

SPEC conducted research flights with an instrumented Learjet aircraft in the U.S. in 2017 and the UAE in 2019. In this section we initially discuss the composite microphysical characteristics of cumulus congestus (CuCg) clouds investigated in 2019. This presentation is followed by a discussion of the possibility of enhancing rainfall from CuCg clouds in the UAE.

Figure 23 shows particle size distributions (PSDs) from cloud passes in both liquid and mixed-phase regions of CuCg measured by the Learjet in the UAE in 2019. Figure 23a shows drop size distributions (DSDs) in all-liquid (ice-free) updrafts and Figure 23b shows PSDs in mixed-phase CuCg clouds. The mean of the DSDs is shown by the black trace in each panel. Very weak coalescence is demonstrated by the rare SLDs formed in the tail shown in Figure 23a. In contrast, as shown previously in Figure 17, the concentration of millimeter-diameter drops in Caribbean CuCg, where there is a strong coalescence process and SIP, is more than two orders of magnitude larger than in UAE CuCg.

The “rainbow” color scheme in Figure 23c corresponds to temperature, where the blueish PSDs are mostly liquid and the reddish PSDs are mixed-phase. The larger particles are ice that is mostly composed of aggregates with some graupel particles. The aggregates are not sufficiently dense to fall rapidly and melt just before reaching the ground, so typically they do not contribute rain on the ground (Cooper and Lawson 1984). The (2 to 3 mm) graupel particles do have a higher terminal velocity and can melt to form precipitation below cloud base, but they are generally too small to prevent them from evaporating before reaching the ground. The result is a very inefficient rain process that does not significantly enhance ground water. The largest hygrometeors in UAE CuCg are found in the form of aggregates and some graupel particles, which is illustrated in the comparison of the mean all-liquid DSD and mixed-phase PSD shown in Figure 23d.

The Learjet investigated mixed-phase regions of UAE CuCg clouds in an attempt to determine the origin of ice in updrafts. Several penetrations were conducted within 200 to 500 m below growing cloud tops to search for the origin of the first ice particles. The results are not altogether conclusive, but the data strongly suggest that ice is formed in CuCg at temperatures warmer than – 15 °C and is transported to warmer regions of cloud via downdrafts at the edges of the updrafts. This is consistent with the observations and modeling studies of UAE CuCg clouds (Moser and Lasher-Trapp 2014; Morrison et al. 2020), which shows that the updrafts are a chain of thermal bubbles that rise, entrain dry air and form negatively buoyant downdrafts at the edges of the bubbles (see Figure 19).

Figure 24 shows scatterplots of pass-average values of total particle concentration (Figure 24a), effective radius (R_{eff} , Figure 24b) and LWC (Figure 24c) for the cloud penetrations shown in Figure 23c. There is a clear trend for particle concentration to decrease and R_{eff} to increase with decreasing temperature (increasing altitude). Without significant coalescence, these trends are likely due to entrainment of dry air, which is supported by the plot of adiabatic LWC shown in Figure 24c. There is no distinct trend in LWC with temperature, which is likely due to entrainment and sampling variability.
Figure 23. a) DSDs in all-liquid regions, b) PSDs in mixed-phase regions, c) both liquid and mixed-phase PSDs where the color scheme proceeds from warmer (blueish) to colder (reddish) colors, and d) mean values of liquid and mixed-phase regions of CuCg clouds investigated in the UAE in 2019.
Figure 24. Scatter plots of a) total particle concentration, b) effective radius ($R_{\text{eff}}$) and c) liquid water content (LWC) from Learjet measurements in CuCg clouds investigated by the Learjet in the UAE in 2019.
Modeling Studies

Modeling of the August 12, 2019 UAE cumulus cloud case study

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Goals. In this study, we simulate the cumulus clouds observed during the August 12, 2019 case in the UAE using a large eddy simulation model coupled with bin microphysics. The main goals are to use the model in conjunction with observations to understand processes controlling evolution of drop size distributions (DSDs) and large drop generation, and to evaluate the model using aircraft observations.

Model setup. We simulate the UAE SF-1 (August 12, 2019) case study that was observed by the SPEC Learjet near the foothills of the Al Hajar Mountains. For this work we use the Cloud Model Version 1 (CM1; Bryan and Fritsch 2002) implemented with a bin microphysics scheme (implementation in CM1 was done by Dr. Kamal Kant Chandrakar at NCAR): the Tel Aviv University scheme (TAU, Tzivion et al. 1987; Feingold et al. 1988; Stevens et al. 1996; Rotach and Zardi 2007). A quasi-idealized three-dimensional model setup is used with a domain that extends 21.6 km x 21.6 km horizontally and 11 km vertically. The horizontal and vertical grid spacings are 100 m and the time step is 1 s. Radiative transfer is neglected and the upper and lower boundary conditions are free slip. The lateral boundary conditions are periodic.

Convection is initiated in the conditionally unstable environment similar to the approach of Lasher-Trapp et al. (2005). During the first hour of the simulations surface latent and sensible heat fluxes are uniform in space and time, building up a deep, turbulent boundary layer that extends to a height of about 3 km. After the first hour the surface fluxes are specified to have a Gaussian shaped spatial distribution with a characteristic horizontal scale of 1700 m. This focuses convergence within the boundary layer and initiates cumulus convection in the center of the domain. The simulations last 2 hours which is sufficient time for several cloud thermals to rise from the boundary layer, grow, and ascend to a relatively stable layer around 8 km, above which the convection rapidly decays. The initial thermodynamic sounding is generated from aircraft measurements from near the surface at 966 mb to 409 mb, above which we use data from the OMAA (Abu Dhabi) sounding at 12Z on August 12, 2019. The aircraft and Abu Dhabi sounding profiles are matched so as to preserve vertical gradients of potential temperature by adjusting the Abu Dhabi sounding uniformly by -3.7 K. The relative humidity is taken directly from the unadjusted measurements. Horizontal wind is derived from the Abu Dhabi sounding with some idealization: winds are set to zero in the lowest 1 km above ground level and winds above this height are smoothed with a running mean over the surrounding 10 sounding measurements at a given level. Vertical wind shear for this case overall is fairly weak.

The TAU microphysics scheme solves equations for number and mass mixing ratios in 35 mass doubling bins. It includes processes for droplet activation on an input aerosol distribution (currently assumed constant in time and space), condensation growth, evaporation, collision-coalescence of drops, and their gravitational settling. Only liquid microphysics is included; ice-phase hydrometeors are neglected. From the aircraft observations, ice particles were present in “old” cloud turrets but there was almost no ice present in newer, actively growing turrets.

To understand the microphysical processes driving evolution of the DSDs for this case a handful of sensitivity tests were run with the model and analyzed (see Table 1). These include tests with:
collision-coalescence turned off, activation of new droplets above cloud base turned off, and with the input aerosol concentration reduced by a factor of 10 to represent a pristine environment.

**Table 1.** Summary of the four simulations discussed in this writeup.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Standard TAU scheme implemented in CM1, includes collision-coalescence</td>
</tr>
<tr>
<td>NOCOAL</td>
<td>As in Control except collision-coalescence is turned off</td>
</tr>
<tr>
<td>LOWCCN</td>
<td>As in Control except the input aerosol number concentration is reduced by a factor of 10</td>
</tr>
<tr>
<td>BASEONLY</td>
<td>As in Control except droplet activation turned off above 4 km (above ground level) so only droplet activation near cloud base is allowed</td>
</tr>
</tbody>
</table>

**Results from the Control simulation.** The control simulation produces a deep boundary layer with a top approximately 3 km above ground level. Moist convection is initiated around 85 min near the center of the domain, driven by the enhanced surface fluxes in this region (upper left plot in Figure 1). Subsequently, the moist convection deepens rapidly as seen by the vertical cross section profiles of vertical velocity and cloud boundary at various times (Figure 1). Cumulus convection is rooted in a steady plume-like updraft in the boundary layer that is driven by the surface fluxes. Above the level of free convection (appr. 4 km) distinct thermal-like circulation features emerge and rise up to the level of relative stability around 8 km, above which they decay. These thermal features are seen in Figure 1 as local regions of maximum vertical velocity within the cloud, with weaker ascent or even small pockets of descent between individual thermals. The thermals rise in succession consistent with the “thermal chain” structure of cumulus convection described by Morrison et al. (2020) and Peters et al. (2020). These thermals are associated with cloud turrets as observed by the Learjet aircraft. The maximum vertical velocity in the Control simulation is 16.8 m s⁻¹, close to the maximum of 18 m s⁻¹ observed by the Learjet during the -12°C flight penetration in the “new” turret (though the model maximum occurs about 1 km lower).
only a portion of the model domain is shown. Red squares, circles, and triangles show the approximate locations of individual thermals as indicated by local vertical velocity maxima. Cross sections are taken at the center of the model domain.

Vertical cross sections of the cloud microphysical structure for the Control simulation at 105 min are shown in the top panel of Figure 2. Liquid water content (LWC) has considerable variability, with local maxima occurring near the vertical velocity maxima associated with individual cloud thermals. LWC is relatively small near the bottom of individual thermals and between them, presumably due to entrainment and mixing. Morrison et al. (2020) and Peters et al. (2020) document how entrainment is locally enhanced near the bottom of individual rising thermals. While there is considerable variability of LWC associated with these dynamical features, there is a general increase with height consistent with
condensational growth of droplets in ascending air. LWCs reach a maximum of 2-3 g m\(^{-3}\) between 7 and 8 km, which agrees well with the maximum LWC of 2.2 g m\(^{-3}\) (average LWC = 1.5 g m\(^{-3}\)) from aircraft observations for a penetration at -12\(^\circ\)C (approximately 7 km height). However, given the substantial scallop-scale variability of LWC, it is unclear if the slightly higher LWC in the model is simply due to limited sampling by the aircraft.

Droplet number concentration \(N_c\) is generally between 600 and 650 cm\(^{-3}\) near cloud base (center top plot in Figure 2). This is in good agreement with the observations, which showed an average of 612 cm\(^{-3}\) and a standard deviation of 172 cm\(^{-3}\). \(N_c\) decreases to generally between 350-450 cm\(^{-3}\) at 7 km near the -12\(^\circ\)C aircraft penetration level, similar to the observed value of 406 cm\(^{-3}\). Droplet mean volume diameter \(D_m\) (right upper plot in Figure 2) shows a general increase with height as expected from droplet growth that is dominated by condensation. Again, there is some smaller-scale variability in \(D_m\) associated with the thermal structures and smaller-scale dynamical features. Note the area of large \(D_m\) exceeding 36 \(\mu\)m (small red region in the upper right plot in Figure 2) is from the production of larger drops by collision-coalescence. As detailed below, collision-coalescence is very limited in the model for this case but there is enough to produce regions with low concentrations (about 0.01 to 0.1 L\(^{-1}\)) of drops with diameter > 100 \(\mu\)m.

**Figure 2.** Vertical cross sections of LWC (left), droplet number concentration \(N_c\) (center), and mean volume diameter \(D_m\) (right) for the Control simulation (top panel) and BASEONLY simulation (bottom panel) at 105 min. In all plots the black contour lines indicate vertical velocities of 5, 10, and 15 m s\(^{-1}\). Only a portion of the model domain is shown. Cross sections are taken at the center of the model domain.
The microphysical features seen in Figure 2 are also evident in a statistical analysis of the simulated cloud. Figure 3 shows vertical profiles of mean, mean plus one standard deviation, and maximum LWC, Nc, and Dm calculated between 100 and 120 min including all points with Nc > 10 cm^-3. The Control simulation, shown by black lines, produces LWC that increases somewhat with height, though not monotonically, with a steadier decrease in Nc and increase in Dm, with height. Small-scale dynamical variability in addition to temporal evolution of the cloud (namely, the rising thermal structure) drives significant variability in the microphysical fields, particularly LWC but less so for Dm, seen by the spread between the mean, mean plus one standard deviation, and maximum values at a given height.

**Figure 3.** Vertical profiles of LWC (left), droplet number concentration Nc (center), and mean volume diameter Dm (right) for the 4 simulations: Control (black), NOCOAL (blue), LOWCCN (red), and BASEONLY (green). Thick solid lines show mean values, thin solid lines are mean plus one standard deviation, and dotted lines show maximum values over the period from 100 to 120 min. All points with Nc > 10 cm^-3 are included in the statistics.

Finally, we compare the drop size distributions simulated from the Control simulation with those obtained from the Learjet cloud penetrations. We focus on the four aircraft penetrations of active cloud turrets at temperatures of approximately 9.5°C (just above cloud base), 4°C, 2.6°C, and -12°C. Modeled DSDs at each grid box where LWC > 0.1 g m^-3 and within 0.5°C of a given flight penetration temperature (which encompasses one or two model vertical levels for each penetration) are shown in Figure 4 (black lines) along with the observed DSDs (red lines). Overall, the model does a reasonable job of simulating the observed DSDs. The main difference is the lack of medium-sized drops (between 20-100 mm). This bias is particularly evident near cloud base, but persists to a lesser extent up to the 4°C and 2.6°C levels as well. For the -12°C flight penetration the model does a better job capturing low concentrations of medium to large drops (up to a 1.5 mm) that were observed. However, note concentrations are very low for both the modeled and observed DSDs (about 9 orders of magnitude lower than the peak of the DSDs). The concentration of drops with diameter larger than 100 μm in the Control simulation increases over time if the simulation is extended past 2 hours, mainly lower in the cloud from the sedimentation of larger drops produced aloft. After about 2 hours 20 min, the model generates drops having diameters
between ~0.3 and 3 mm with concentrations up to ~0.01 L⁻¹ at cloud base and below; and light surface precipitation eventually reaches the surface. However, we caution placing much emphasis on these results because the model setup is not designed to address later stages of cloud evolution (thus, why we limited most of the simulations and analysis to 2 hours). Specifically, the surface flux forcing is held fixed in time after 1 hour. This generates strong sub-cloud convergence and continuous generation of new cloud thermals over the same location which did not occur in reality over the full cloud lifetime (order 1 hour). Thus, the model is best suited for studying the evolution of earlier cloud thermals.

Results from the sensitivity tests. Several sensitivity experiments have been conducted to understand better the processes driving the microphysical and dynamical behavior of the simulated cloud; see Table 1. The general lack of collision-coalescence in this cloud is demonstrated by the test with collision-coalescence turned off (NOCOAL). This simulation produces both macro-scale cloud structure and microphysical behavior very similar to the Control simulation (which has collision-coalescence turned on). This is evident from vertical profiles of the mean, mean plus one standard deviation, and maximum
LWC, \(N_c\), and \(D_m\) (compare the blue and black lines in Figure 3), as well as the DSDs (compare Figures 4 and 5). The main difference between the NOCOAL and Control runs is the complete lack of medium and large drops in NOCOAL, particularly at the -12°C level. Thus, while collision-coalescence is evidently very limited for this case, it does occur in the Control simulation and explains the large drop mode seen in the lower right plot in Figure 4.

![Figure 5](image)

**Figure 5.** As in Figure 4 except for the NOCOAL simulation.

Very limited collision-coalescence for this case is potentially explained by a few features: 1) high cloud base and thus fairly narrow region for warm rain production; 2) high CCN and hence droplet concentrations; 3) lack of giant CCN in the model (although giant and ultra-giant CCN were seen below cloud base in the observations). To test these explanations, we ran a sensitivity test with the input aerosol concentration reduced by a factor of 10 (LOWCCN). As expected, this test produces much lower droplet concentrations \((N_c < 100 \text{ cm}^{-3})\) and correspondingly large \(D_m\) values that exceed 40 \(\mu\text{m}\) at mid cloud levels (red lines in Figure. 3). LWC is greater at low cloud levels and lesser at upper levels compared to the Control simulation, which probably reflects dynamical changes to the cloud. Namely, cloud evolution is delayed by about 10-15 min in LOWCCN and thus the cloud top tends to be lower at a given time compared to the Control. This might be due to decreased buoyancy in LOWCCN associated
with the lower N_c and longer phase relaxation time, resulting in reduced latent heating rates (e.g., Grabowski and Morrison 2017, 2020; Fan et al. 2018). However, the robustness of this result is unclear and ensembles with multiple realizations are needed to confirm this as a general finding. Besides the reduced concentration of small drops in LOWCCN, there is ample production of medium and large drops from collision-coalescence as seen by the DSDs in Figure 6. Concentrations of drops with diameter > 50 μm are greater than observed by up to 1 to 3 orders of magnitude above cloud base, particularly for the 2.6 and -12°C flight penetrations. In this simulation these large drops fall to cloud base and below. Thus, despite a relatively shallow region for collision-coalescence and lack of any giant CCN, the model is able to produce fairly vigorous production of large drops via collision-coalescence if the droplet concentration is low enough. This occurs because low drop concentrations allow for much faster growth via condensation, which enhances collision-coalescence growth later. For example, previous observational studies have indicated that droplet effective radius must exceed about 14 μm for significant collision-coalescence to occur (e.g., Rosenfeld and Gutman 1994; Geber 1996; Freud and Rosenfeld 2012).

Next, we investigate factors that control the evolution of N_c in the simulated cloud. The Control simulation shows a decrease of N_c from > 600 cm⁻³ near cloud base at 3.5 km to roughly 400 cm⁻³ at 7 km (near -12°C), which was also evident from the observations. There are three possible explanations for this decrease of N_c with height: 1) collision-coalescence; 2) dilution from entrainment and mixing; 3) expansion of rising air parcels and the decrease of air density with height. As discussed above, profiles of N_c are very similar between the Control and NOCOAL simulations, ruling out collision-coalescence as being important in controlling N_c for this case. The effects of decreasing air density are simple to estimate, with the density near 7 km approximately 75% of that near cloud base implying a 25% reduction of N_c between 3.5 and 7 km. The decrease of air density can therefore account for most but not all of the decrease in N_c with height. On the other hand, we know that entrainment and dilution from mixing of cloudy and cloud-free air is substantial. This is evident, for example, by the fact that LWC in all of the simulations (and in the observations) is generally much smaller than the adiabatic LWC despite little removal of condensate from sedimentation (at least, in the Control and NOCOAL runs).

How can we reconcile significant entrainment and cloud dilution with the fact that N_c decreases only somewhat beyond the expected change simply from decreasing air density? This is explained by the activation of new cloud droplets well above cloud base which compensates for the reduction of N_c by entrainment and dilution. This is demonstrated by the BASEONLY test, in which cloud droplet activation above 4 km (0.6 km above cloud base) is turned off. This simulation shows a sharp decrease of N_c above 4 km and much larger values of D_m (green lines in Figure 3) than in the Control. The sharp decrease of N_c in BASEONLY is also seen in vertical cross-sections of the microphysical fields (bottom panel in Figure 2). This decrease of N_c has a significant impact on the dynamics, because cloud free air that is entrained above 4 km and ascends and adiabatically cools to its saturation point will remain cloud free and supersaturated unless existing cloud droplets are mixed into this air. As a result, the cloud as a whole tends to break apart with large cloud-free gaps between the individual thermals comprising the cloud. We emphasize that this test is extreme; in nature, aerosols will almost always be present to activate cloud droplets given sufficient supersaturation, especially for “fresh” environmental air entrained into a cloud that has not been scavenged of aerosols. With the low droplet number concentration aloft in BASEONLY there is much more warm rain generation from collision-coalescence compared to the Control simulation. This is evident from the DSDs at the four aircraft penetration levels in BASEONLY (Figure 7). Except for the 9.5°C level near cloud base in the upper left plot of Figure 7, the concentration of small drops (< 10-20 μm) is much less than observed or produced by the Control simulation. This points to the critical importance of in-cloud droplet activation well above cloud base in maintaining high
concentrations of small droplets in the Control simulation (and, presumably, the observed cloud). Finally, we note that the Control simulation likely represents an upper bound for the in-cloud activation of cloud droplets because we do not account for scavenging and in-cloud removal of aerosols explicitly.

**Figure 6.** As in Figure 4 except for the LOWCCN simulation.
Preliminary conclusions of modeling studies.

The main conclusions resulting from this work are as follows:

- Overall the model does a good job of reproducing the general cloud structure and microphysical features observed by the Learjet. The main bias (in the Control simulation) is a lack of medium sized drops (30-100 $\mu$m), particularly lower in the cloud, which likely results from neglecting giant CCN in the model.
- There is little generation of drops with diameter > 100 $\mu$m from collision-coalescence in the simulated cloud, though very low concentrations (up to 0.01 to 0.1 L$^{-1}$) of mm-size drops are produced at upper levels (e.g., the -12°C flight penetration) consistent with the observations. Reducing the aerosol loading and hence droplet concentrations by an order
of magnitude is *sufficient* to produce significant collision-coalescence for this case despite the high cloud base and lack of giant CCN in the model. However, it is not clear if a low droplet concentration is *necessary* to generate significant collision-coalescence; it is plausible that including giant CCN could also increase collision-coalescence substantially in the model, but this remains to be tested (see additional work below).

- **Droplet number concentration** $N_c$ decreases with altitude in both the simulations and observations. Much of this decrease is attributable simply to the decrease of air density with height. The decrease of $N_c$ from entrainment and dilution is mostly balanced by in-cloud activation of new droplets well above cloud base. We showed that this in-cloud activation is *critical* in the model for maintaining high concentrations of small droplets ($<10-20$ μm) at mid and upper cloud levels. In turn, by maintaining large concentrations of small droplets aloft, in-cloud droplet activation in the model limits the production of drops larger than 100 μm by collision-coalescence.

### Additional modeling work prior to publication.

**Addressing the role of giant CCN:** Currently the TAU scheme implemented in CM1 is not configured to include giant CCN. Some development work will therefore be needed, namely, to add a sectional representation of aerosols that act as CCN, including giant and ultra-giant CCN (so they are advected and nucleated). By explicitly tracking aerosols of various sizes, this will also improve representation of in-cloud activation in the Control simulation. We do not plan on adding a detailed representation of other aerosol processes such as wet scavenging or new particle formation.

**Further analysis of in-cloud droplet activation:** Given the importance of in-cloud activation above cloud base indicated by the results above, we will further study this process by analyzing model output of droplet activation rates directly. It is hypothesized that in-cloud droplet activation mainly occurs within the inflowing circulation of individual cloud thermals (near the bottom of these thermals), and this analysis will test this hypothesis.

**Ensembles with different realizations:** To improve robustness, run 3-5 ensemble members for each model configuration. Different members will have different random number seeds used to generate small amplitude noise in the initial perturbation potential temperature field.

**Sensitivity to model grid spacing:** The 100 m horizontal vertical grid spacings are near the upper limit of what qualifies as large eddy simulation. To explore this issue, we propose a set of simulations using 50 m horizontal and vertical grid spacings, and possibly even down to 25 m. By decreasing the grid spacing and increasing model resolution, it can better capture entrainment and turbulent mixing processes.
Summary and Recommendations

The overarching purpose of the research was to collect data in cumulus congestus (CuCg) clouds to ascertain if a natural secondary ice process (SIP) could be stimulated by hygroscopic seeding to enhance rainfall. As described in Lawson et al. (2015, 2017), in order for the SIP to occur, CuCg clouds need to develop relatively high concentrations of supercooled large drops (SLDs) that are of order millimeter-diameter via a strong coalescence process. Once a sufficient concentration of SLDs form, freezing of a few drops produces drop-fracturing and copious small ice particles that collide with other SLDs, inducing an avalanche process that effectively seeds the supercooled portion of the cloud and enhances rainfall.

In CuCg clouds that naturally produce high concentrations of SLDs, such as in the maritime tropics, the natural SIP is active and no further stimulation via hygroscopic seeding has a beneficial effect. In CuCg clouds that only produce small supercooled drops (< 100 µm diameter), such as over most of the High Plains in the U.S., hygroscopic seeding is incapable of producing SLDs and therefore the SIP cannot become active. However, in some locations where a weak coalescence process is active, but insufficient to produce warm rain or a SIP (such as in the UAE), it may be possible to stimulate the coalescence process to generate a SIP and enhance rainfall.

Data from the 2019 UAEREp project and modeling studies (Morrison 2020) indicate that CuCg clouds in the UAE generate a very weak coalescence process that is insufficient to produce warm rain or significant SIP. Instead, liquid water is carried aloft in the form of small droplets that evaporate in a very dry environment above cloud base. Results of the airborne and modeling studies (Morrison 2020) suggest that it may be possible to enhance coalescence in UAE CuCg clouds via hygroscopic seeding with the new nano-material. To accomplish this, the data suggest that increasing the concentration of drops in the 10 to 30 size range may boost the coalescence process sufficiently to stimulate a SIP. Currently, the nanomaterial is the only seeding material used in the UAE with a size range extending from 1 to 10 µm, compared to the ICE70 (0.1-1.5 µm) and NCM (0.1-0.3 µm) material size ranges. The extended size range of the nanomaterial may provide enhanced coalescence in the 10 to 30 µm size range of drops sampled just above cloud base. However, this possibility will require additional extensive field tests with seeding and research aircraft.

If UAE CuCg clouds could be properly seeded to enhance the coalescence process, the large drops will not evaporate as rapidly as small cloud drops and can fracture to produce copious ice particles. This can result in a process whereby ice particles produced by fracturing of SLDs collide with and freeze other SLDs, producing an avalanche SIP. Instead of small drops being carried aloft and evaporating, coalescence produces SLDs and a SIP that converts SLDs to graupel particles, which precipitate and melt into rain drops.

Measurements of the new NaCl-TiO₂ nano-material are encouraging, but are not nearly sufficient to predict the outcome of seeding CuCg with the new seeding agent. A reliable delivery mechanism for dispensing the NaCl-TiO₂ needs to be developed and tested. Experiments to determine the dispersion characteristics of the nano-material in the atmosphere and in clouds are needed to see how much of the material will actually be dispersed within cloud. Also, a large dataset of measurements that include aircraft and radar data recorded during a randomized seeding experiment are needed to evaluate the effects of seeding with the new nano-material. Access to Omani airspace where CuCg form over the western foothills of the Al Hajar Mountains will expand the dataset.
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Appendix A: Publications

Publications from Previous Periods


Publications this Period


Publications in Progress


Appendix B: Case Studies

Case studies were generated using data from the four primary Learjet missions conducted during the 2019 UAEREP field campaign (12, 13, 18, 19 August). The first case study included in this Appendix, 12 August, was generated by Dr. Paul Lawson. Dr. Sarah Woods provided case studies for 13 and 18 August and Mr. Youssef Wehbe did a case study analysis of 12 and 19 August. The results contained in the main body of this report are drawn from these case studies.
As shown in Fig. 1, the SPEC Learjet flew a mission on 12 August 2019 that focused on convective clouds located just west of the foothills of the Al Hajar Mountains about 20 km north of Al Ain. The aircraft track to the southwest was required by ATC to climb to 23,000 ft. As shown in Fig. 2, several penetrations of cumulus congestus clouds were conducted from near cloud tops (about -15 °C), down to cloud base at about 9.5 °C. There was also one subcloud pass at 9.9 °C where aerosols were sampled. Figure 3 shows a Skew-T sounding that is comprised of aircraft temperature and dew point temperature measurements from the surface at 966 mb (43.3 °C), to 409 mb (-15 °C), and above that level from the OMAA (Abu Dhabi) sounding from 12Z on 12 August 2019. Analysis of the Skew-T suggests that cloud tops impinged on a stable layer between 400 and 300 mb (-15 to -25 °C) that would have limited vertical development.

Figure 1. Learjet flight track on 12 August 2019.
Figure 2. 3D flight track of the Learjet descending from the -12 °C level to the 9.9 °C level, which was just below cloud base at 9.5 °C. The red dots are locations and temperatures where the aircraft penetrated clouds and the red swath shows the region where subcloud aerosol particles were imaged. The thin red line is the aircraft track projected on the surface.
**Figure 3.** Skew-T sounding comprised of aircraft temperature and dew point temperature measurements from the surface at 966 mb (43.3 °C) to 409 mb (-15 °C), and above that level from the OMAA (Abu Dhabi) 12Z sounding on 12 August 2019. Also shown on the diagram is cloud base elevation measured by the Learjet.

**Figure 4** shows CPI images of aerosols collected just below cloud base elevation. The composition of the aerosols is unknown, but they appear to be a combination of dust with some larger botanical particles.
A PSD combining PCASP, FCDP and 2D-S data from the same time period as Fig. 4 is shown in Fig. 5. While the majority of particles are in the 0.1 to 0.5 µm size range, there are very low concentrations of aerosols that extend out to about 200 µm. Typically, this type of very broad aerosol distribution at cloud base is required to help initiate the coalescence process (refs).

Figure 4. Examples of CPI images of sub-cloud aerosol particles observed in the UAE during the Learjet mission on 12 August 2019.
Figure 5. PSDs from (top) multiple probes (see legend) that measured the aerosol size distribution in the sub-cloud region, and (bottom) composite PSD resulting from joining the PSDs where they overlap.
Figure 6. DSDs from (top) multiple probes (see legend) that measured the size distribution in the region approximately 300 m above cloud base, and (bottom) composite DSD resulting from joining the individual probe DSDs where they overlap.
Drop size distributions (DSDs) from measurements just above cloud base are shown in Fig. 6. Comparison of the size distributions in Figs. 5 and 6 show they are very similar, with the major difference being in the size range from 2 to 30 μm. This is expected if the subcloud aerosols are condensing into cloud drops and growing rapidly at water saturation. As shown in Fig. 7, the cloud base DSD on 12 August is typical of cloud-base DSDs measured in cumulus congestus clouds on other days in the UAE. Also noteworthy is that the clouds studied on 19 August had similar cloud-base DSDs compared with the other three cases located far to the southwest. This is not to say that other types of clouds in the UAE have similar DSDs at cloud base. For example, high-based alto cumulus clouds are disconnected from the surface aerosol layer and will have different microphysical properties. Also, large cumulonimbus cloud systems can have much lower cloud bases and different DSDs.

![Figure 7](image_url)

**Figure 7.** (top) Flight tracks showing the general locations where (bottom) composite DSDs were measured within about 300 m of cloud base elevation on four missions in the UAE.
Figure 8 shows updraft velocity and LWC measurements from a cloud penetration at 4 °C. Updraft velocity peaks at 7 m s⁻¹ and LWC at 1.2 g m⁻³, suggesting that this is a region with a growing turret. Figure 9 shows DSDs within the updraft region and Fig. 10 shows examples of particle images. The DSDs extend only out to 100 µm and the CPI and 2D10 images show only water drops. The relatively narrow DSD at 4 °C indicates a lack of coalescence.

![Graph of updraft velocity and LWC](image)

**Figure 8.** Time series of (top) updraft velocity and (bottom) liquid water content (LWC) measured by the Nevzorov hot-wire in the turret measured at 4 °C on 12 August 2019.
Number Concentration Distribution 20190812--110403-110408

Date: 20190812
39843 <= Seconds < 39848
110403 <= hh:mm:ss < 110408

Particle Size (μm)

Concentration (L⁻¹ μm⁻¹)

- FSSP 1Hz
- 2D10M4M7H
- 2D50M4M7H3V

Composite ISD 20190812-110403-110408

Concentration (#/L/m²)

Time: 110403 to 110408

Probes: FSSP 1Hz—2D10M4M7H—2D50M4M7H3V—none
Break points: 4.5, 12, 7, 100, 100

Drop Size (μm)
Figure 9. DSDs from (top) multiple probes (see legend) that measured the size distribution in a turret at 4 °C on 12 August 2019, and (bottom) composite DSD resulting from joining the individual probe DSDs where they overlap.

Figure 10. Examples of CPI and 2D10 images observed during penetration of a turret at 4 °C on 12 August 2019.
Figure 11 shows a time series of updraft velocity and LWC for a cloud penetration at 2.6 °C, and Fig. 12 shows DSDs from the same penetration. There is very little difference in the microphysical and dynamic properties between the cloud penetrations at 4 and 2.6 °C.

Figure 11. Time series of (top) updraft velocity and (bottom) liquid water content (LWC) measured by the Nevzorov hot-wire in the turret measured at 2.6 °C on 12 August 2019.
Figure 12. DSDs from (top) multiple probes (see legend) that measured the size distribution in a turret at 2.6 °C on 12 August 2019, and (bottom) composite DSD resulting from joining the individual probe DSDs where they overlap.
The Learjet penetrated a supercooled cloud at −6 °C in a dissipating turret. Figure 13 shows that the sample was in a -3 to -5 m s⁻¹ downdraft with a maximum of 0.25 g m⁻³ LWC. There were no supercooled large drops observed by any of the imaging probes. Figure 14 shows representative imagery and Fig. 15 shows PSDs from the penetration. It is readily apparent from the particle imagery that this is a mixed-phase region of cloud. The images were collected in a weak downdraft that was likely newly-formed. The age of the downdraft cannot be accurately determined, but can be estimated by the observation that supercooled cloud droplets are still present (Fig. 14.). The imagery and PSD suggest that the downdraft is composed of a high verity of ice particle types, ranging from small ice crystals to large aggregates and up to 3-mm diameter graupel.

![Graph](image)

**Figure 13.** Time series of (top) updraft velocity and (bottom) liquid water content (LWC) measured by the Nevzorov hot-wire in the turret measured at -6 °C on 12 August 2019.
Figure 14. Examples of (a) CPI, (b) 2D10 and (c) 2D50 images observed during penetration of a turret at -6 °C on 12 August 2019.
Figure 15. PSDs from (top) multiple probes (see legend) that measured the size distribution in a turret at -6 °C on 12 August 2019, and (bottom) composite PSD resulting from joining the individual probe PSDs where they overlap.
The next two cloud penetrations occurred at about the –12 °C level, but in turrets with very different characteristics and in their point of development in terms of cloud lifetime. Aircraft penetrations and forward video observations suggest that vertical development in some clouds was capped at about the -15 °C level, while other clouds were able to penetrate this level. Figure 16 shows time series of measurements from cloud penetrations at –12 °C when the updraft velocity was zero or negative (labeled Old Turrets), and when the updraft velocity peaked at 18 m s⁻¹ (labeled New Turret).

**Figure 16.** Time series of (top) updraft velocity and (bottom) liquid water content (LWC) measured by the Nevzorov hot-wire in the turret measured at -12 °C in “Old Turrets” and a “New Turret” on 12 August 2019.

**Figure 17** shows photographs of the Old Turrets and New Turret prior to cloud entry. The thermodynamic sounding in Fig. 3 shows a very strong inversion at about the -15 °C level. Measurements from the turrets penetrated from 105833 – 105852 shown in Fig. 3 suggest that those
turrets did not have sufficient momentum to penetrate the inversion and likely were in the process of dissipating. The particle size distributions (PSD) from these turrets show an inflection where most of particles larger than about 100 μm are ice (Fig. 18). This is demonstrated by examples of particle images from the CPI, 2D10 and 2D-50 probes, shown in Figure 19. The CPI images are mostly small water drops with occasional ice particles. This is due to the small CPI sample volume and relatively high concentration of water drops compared to the larger ice particles. However, the 2D10 and 2D50 probes, which have larger sample volumes and data rates, clearly show ubiquitous irregularly-shaped ice particles.

Figure 17. Photos of (a) the “Old Turrets” and (b) “New Turret” as identified in the time series in Fig. 16 prior to cloud entry. Arrow points to a pileus above the rising turret.
Figure 18. PSDs from (top) multiple probes (see legend) that measured the size distribution in “Old Turrets” (Figures 16 and 17a) at -12 °C on 12 August 2019, and (bottom) composite PSD resulting from joining the individual probe PSDs where they overlap.
Figure 19. Examples of CPI and 2D10 images observed during penetration of dissipating turrets at -12 °C on 12 August 2019.
In contrast, the penetration of the “New Turret” at about 110030 in Fig. 16 has an updraft that peaks at 18 m s$^{-1}$, which is substantiated by a pileus on the rising turret in Fig. 17. The PSD in Fig. 20 shows particles out to about 1 mm, but the shape of the distribution is much different than observed in the dissipating turret. The dissipating turret has an inflection between 0.1 and 1 mm that is attributable to ice particles (see Figs. 18 and 19). The active turret is composed of all water drops. There is only a single 1-mm drop in thousands of HVPS images and the largest drop found in the 2D50 images is about 500 µm (Fig. 21). There do not appear to be enough supercooled large drops to support a coalescence process.

Figure 20. PSDs from (top) multiple probes (see legend) that measured the size distribution in a “New Turret” (Fig. 16) at -12 °C on 12 August 2019, and (bottom) composite PSD resulting from joining the individual probe PSDs where they overlap.
Figure 21. Examples of (a) CPI, (b) 2D10 and (c) 2D50 images observed during penetration of a “New Turret” (Fig. 16) turret at -12 °C on 12 August 2019.

The comparison of microphysical properties between the dissipating (“Old”) turrets and active (“New”) turret (see Figs. 16 and 17) sampled at -12 °C within about 15 km and 2 min flight time of each other (Fig. 2), is striking. The difference may be attributable to the extra momentum that the active turret possessed that enabled it to penetrate the stable layer between -12 and -15 °C. The active turret can be the result of several factors, such as a stronger thermal bubble rising from below, less dry air entrainment and less precipitation loading, or a combination of all three factors.
UAE SF-2 (13 August 2019) Case Study

Sarah Woods
SPEC Incorporated

On 13 August 2019, the Learjet flew a mission that focused on sampling of convective clouds in the same location as SF-1, as shown in Fig 1. There were fewer clouds in the area, but the same procedure was followed: the Learjet flew out of Al Ain to the southwest, into the military area and climbed to 23 kft. On the climb, the Lear made a few penetrations of an alto layer and some convective elements embedded in the alto layer between -6 and -8 °C (see location in Fig. 2). These clouds provided the only ice particles observed during this flight. At 23 kft, a couple of altocu were penetrated at cloud top (-11 °C), composed of all small drops. The Lear then returned to the area of interest on the Oman border, looking for candidate clouds. There was one convective candidate that was growing above the Lear flight level, but the crew was not able to penetrate the candidate due to air traffic. The Learjet subsequently penetrated convection from 18 kft (-6 °C) to cloud base (8.5 °C), all in the warm region, providing evidence of a weak coalescence process in the sampled clouds.

Figure 1. Learjet flight track on 13 August 2019 showing climbout toward the southwest up to 23kft, then returning to sample convection near the Oman border.
Figure 2. 3-D flight track showing location of Learjet cloud penetrations and associated temperature levels.
Figure 3. Skew-T sounding comprised of the OMAA (Abu Dhabi) 12Z sounding on 13 August 2019. Noted is the stable layer from about 350 – 570 mb. Cloud base elevation measured by the Learjet is at the bottom of the indicated stable layer.

Figure 3 shows the 12Z Skew-T plot from the OMAA (Abu Dhabi) sounding on 13 August 2019. As on 12 August, analysis of the Skew-T suggests that cloud tops impinged on the stable layer would have limited vertical development.

Figure 4 shows CPI images of aerosols collected just below cloud base elevation from (left) climbout, when no local clouds were present directly above, and (right) descent toward Al Ain, immediately after the Learjet sampled cloud base DSDs. The composition of the aerosols is unknown, but as in SF-1 on August 12, they appear to be a combination of dust with a mix of some botanical particles. A set of overlay and composite sub-cloud aerosol PSDs from the PCASP, FCDP, 2D-S, and Hawk-2D50 taken from the time period immediately after sampling cloud base are shown in Figure 5. Again, similarly to the
flight on 12 August, while the majority of particles are in the 0.1 to 0.5 μm size range, there are very low concentrations of aerosols that extend out to about 200 μm. Typically, this type of very broad aerosol distribution at cloud base is required to help initiate the coalescence process.

**Figure 4.** CPI images of sub-cloud aerosol observed just below cloud base height on 13 August 2019, from (left) climbout and (right) descent.
Figure 5. (Top) Overlay and (bottom) composite from several instruments (PCASP, FCDP, 2D-S, and Hawk-2D50) of aerosol PSDs observed just below cloud base on return toward Al Ain.
Figures 6-8 show observations from penetration of the ragged cloud base at 8.5 °C, collected just prior to the sub-cloud aerosol observations of Figs 4-5. Fig. 6 shows CPI and 2D-S imagery from the cloud base pass, which is composed of mostly small drops with the occasional 400-500 μm drop. The corresponding time series of updraft velocity and LWC are plotted in Fig. 7. The updraft velocity is fairly typical of cloud base, averaging around 1 m s⁻¹, with liquid water around 0.1 – 0.3 g m⁻³. The overlay of all instrument PSDs and a composite of combined instrument PSDs are shown in Fig. 8. As expected given the sub-cloud aerosol distribution in Fig. 5, the cloud base DSD extends to about 70 - 80 μm. The DSD includes a tail, however, to indicate the presence of occasional larger precipitating drops extending to 0.5 mm, as seen occasionally in the OAP imagery (Fig. 6). The presence of precipitation at cloud base is not surprising given cloud base was sampled later on in the flight, in a cloud that was already well-developed, where weak coalescence was already observed at higher levels in cloud, as shown in subsequent figures.

Figure 6. Sample (left) CPI, (right) 2D-S images from a pass near ragged cloud base showing mostly small drops.
Figure 7. Time series of (top) updraft velocity and (bottom) LWC for pass near cloud base.

Figure 8. (Left) Overlay and (Right) composite of individual instrument PSDs near cloud base (8.5 °C) showing DSD extending to about 70 µm, interspersed with occasional larger drops extending to 0.6 mm.

At the higher altitudes of this flight, the Learjet sampled convective portions of an altocu layer. Observations of the altocu at -7 °C are shown in Figs 9-11. CPI imagery suggested all small drops. 2D-S imagery is composed of lots of small drops and rare 200-300 µm ice. Other than the occasional out-of-cloud ice fallout from some cirrus in transit portions of the flight, these are the only ice crystals observed during the course of the flight. Flight video suggests it was rather clear overhead, and another nearby
alto layer at -11 °C indicated all small drops, so it is unclear where these ice crystals came from. As shown in Fig. 10, the updraft here was fairly weak, ranging from 0-2 m s⁻¹, with a continuous LWC of 0.3 g m⁻³ for 12 seconds. The corresponding PSDs, plotted in Fig. 11, also resemble observations at cloud base, with a narrower drop distribution extending to near 80 µm, and a tail indicating the larger precipitating particles, in this case irregularly shaped ice particles.

**Figure 9.** Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images from sampling convective elements in alto layer showing all small drops and the occasional 200-300 µm ice particle.
**Figure 10.** Time series of (top) updraft velocity and (bottom) LWC.

**Figure 11.** (Left) Overlay and (Right) composite of individual instrument PSDs at -7 °C showing population of small drops, interspersed with occasional larger ice crystals.
As the Learjet returned to the area of interest near the Oman border, the crew began looking for candidate convective clouds. The Learjet subsequently penetrated convection from transit altitude to cloud base, all in the warm region, providing evidence of a weak coalescence process in the sampled clouds. Observations from the first penetration, at 0 °C, are shown in Figures 12-14. As plotted in Fig. 13, this penetration had a strong updraft in the first part of the pass (7 m s⁻¹), which gave way to a more variable updraft across the middle, followed by a second strong peak (6 m s⁻¹). The updraft profile is mirrored in the LWC, with peaks near 0.4 - 1.3 g m⁻³ at the edges of the pass, and near 0 g m⁻³ across the middle. The CPI, 2D-S, and Hawk2D50 imagery in Fig. 12 shows all smaller drops with the occasional 300-500+ µm drop. Correspondingly, the PSDs plotted in Fig. 14 show a somewhat narrow distribution across the smaller drop sizes (out to about 100 µm), with a little more developed large drop tail extending to 2 cm, with a notable bump around 100-300 µm. These observations suggest the presence of weak coalescence in the observed clouds.

Figure 12. Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images showing all small drops and the occasional 300-500+ µm drop.
Figure 13. Time series of (top) updraft velocity and (bottom) LWC.

Figure 14. (Left) Overlay and (Right) composite of individual instrument PSDs from pass at 0 °C.

The Learjet next made a penetration at 1 °C, encountering a moderate updraft of 5 m s⁻¹ lasting a few seconds with a solid 1.3 g m⁻³ in LWC. The observations, shown in Figs. 15-17 show similarly small
drops dominating the CPI imagery, with a slight increase in the occasional drops of 0.5 – 1 mm in diameter observed in the 2D-S imagery. Correspondingly, the PSDs plotted in Fig 17 show a slight broadening of the distribution across the smaller sizes (< 100 µm), and filling in around the previous bump and tail for D > 100 µm, again suggesting weak coalescence.

**Figure 15.** Sample (top) CPI, (middle) 2D-S10, and (bottom) 2D50 images showing small drops and the occasional 0.5 – 1 mm diameter drop.
At 4 °C the Learjet made a long penetration, first encountering mostly downdraft with a LWC of 0.5 g m⁻³, followed by a moderate updraft of 4 m s⁻¹ with several seconds of 1.1 g m⁻³ of liquid water, as plotted in Fig. 19. Fig. 18 shows the particle imagery: CPI small drops out to 100 µm in diameter, 2D-S
small drops with a rare 0.5 – 1 mm drop. The composite PSD shown in Fig 20 remains pretty similar to that of the previous pass shown in Fig. 17, with perhaps a bit of additional filling in around the 100-33 µm bump so that it is less distinguishable from the tail than it was previously.

**Figure 18.** Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images showing CPI drops out to 100 µm and 2D-S small drops with rare 0.5 to 1mm drops.
Figures 21-23 show Learjet observations from penetration at 4.5 °C: another long pass with initially a downdraft (min -2 m s⁻¹ down, 0.1 - 0.5 g m⁻³ liquid water), followed by a moderate updraft (max 3 m s⁻¹ up, 1.0 g m⁻³ liquid water). CPI was operated in fishing mode for this penetration to allow
for increased capture of particle images with D > 50 μm. As a result, the CPI images in Fig. 21 look larger than in other passes, showing drops out to 350 μm. The 2D-S and Hawk2D50 imagery again shows an abundance of smaller drops, with occasional 200-400 μm drops. The composite PSD for this pass shows a narrower drop distribution across the smaller sizes (D < 80 μm), with the middle-sized bump across 100 – 300 μm again more pronounced.

Figure 21. Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images showing small to moderately sized drops.
Figure 22. Time series of (top) updraft velocity and (bottom) LWC.

Figure 23. (Left) Overlay and (Right) composite of individual instrument PSDs observed from pass at 4.5 °C.

The convective clouds sampled on the 13 August 2019 UAE flight show moderate development and a weak coalescence process. Although strong updrafts (up to 7 m s⁻¹) were encountered on some penetrations of these clouds, no strong coalescence was observed, and these clouds did not reach sufficient development to form ice. Development of these clouds was likely capped by the strong stable layer, and development may have been further influenced by entrainment of dry air. Strongly developing turrets were observed in proximity during this flight, as shown in the photo of Figure 24, but
the location of these stronger convective clouds was out of reach beyond the Oman border. Turrets similar to those sampled in this flight case study are shown in the foreground of the photo.

Figure 24. Photo showing strong convection (rear of photo) beyond candidate turrets (foreground).
UAE SF-3 (18 August 2019) Case Study

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On 18 August 2019, the Learjet flew a late day mission, from around 16:00 – 18:30 local. The track shown in Figure 1 shows the flight path, taking off to the southwest out of Al Ain, and continuing down to the Saudi border and the Liwa Oases before heading back toward the Oman border and Al Ain. The lead flight scientist commented that he had never seen so many clouds over the UAE, though it was difficult to reach the clouds for sampling at times because they were either just across the border with Saudi or Oman or in restricted UAE airspace. The Lear made penetrations from about -12 °C down to cloud base at the end of the flight, as seen in Figure 2. There was a strong inversion/stable layer around the -5 °C level from 17 to 20 kft, with clear air above and cumulus popping out and rising above the stable layer. The Learjet made a few penetrations above the layer, within the layer, and just below, where lots of dust was observed.

Figure 3 shows the 12Z Skew-T plot from the OMAA (Abu Dhabi) sounding on 18 August 2019. As on 12 and 13 August, analysis of the Skew-T suggests that cloud tops impinged on the stable layer would have limited vertical development.
Figure 1. Learjet flight track on 18 August 2019.
Figure 2. 3-D flight track showing location of Learjet cloud penetrations and associated temperature levels.
Figure 3. Skew-T sounding comprised of the OMAA (Abu Dhabi) 12Z sounding on 18 August 2019. Noted is the stable layer from about 350 – 500 mb. Cloud base elevation is estimated by the Learjet at about 10 °C.

Figure 4 shows CPI images of aerosols collected just below cloud base. The composition of the aerosols is unknown, but as in SF-1 on August 12 and SF-2 on August 13, they appear to be a combination of dust with a mix of some botanical particles. A set of overlay and composite sub-cloud aerosol PSDs from the PCASP, FCDP, 2D-S, and Hawk-2D50 are shown in Figure 5. Again, similarly to the flight on 12 and 13 August, while the majority of particles are in the 0.1 to 0.5 µm size range, there are very low concentrations of aerosols that extend out to about 200 µm. Typically, this type of very broad aerosol distribution at cloud base is required to help initiate the coalescence process, but little evidence of coalescence is observed.
Figure 4. CPI images of sub-cloud aerosol observed just below cloud base height on 18 August 2019.
Figure 5. (Top) Overlay and (bottom) composite from several instruments (PCASP, FCDP, 2D-S, and Hawk-2D50) of aerosol PSDs observed just below cloud base.
Figures 6-8 show observations from penetration about 500 ft above cloud base, near the end of the flight. Some drops are present out to 200 µm, but in very low concentrations. These clouds again show a broad drop distribution that one would expect to support coalescence, but there is very little evidence of it. The FFSSP measures a droplet concentration of 500 cc⁻¹ at cloud base. This looks like a case with too high and cold of a cloud base and too high of a concentration to support strong coalescence. Fig. 6 shows CPI and 2D-S imagery from the pass about 500 ft above cloud base at 9.5 °C, which is composed of mostly small drops with the occasional 100-200 µm drop. The corresponding time series of updraft velocity and LWC are plotted in Fig. 7. The updraft velocity is fairly typical of cloud base, averaging around 3 m s⁻¹, with liquid water around 0.1 – 0.4 g m⁻³. The overlay of all instrument PSDs and a composite of combined instrument PSDs are shown in Fig. 8. As expected given the sub-cloud aerosol distribution in Fig. 5, the cloud base DSD extends to about 200 µm. The domination of the droplet population by small drops is seen in the OAP imagery (Fig. 6).

Figure 6. Sample (left) CPI, (right) 2D-S images from a pass 500 ft above cloud base showing all smaller drops.
Figure 7. Time series of (top) updraft velocity and (bottom) LWC for pass about 500 ft above cloud base.

Figure 8. (Top) Overlay and (bottom) composite of individual instrument PSDs about 500 ft above cloud base (9.5 °C) showing DSD extending to 200 µm.

Some of the clouds sampled on this flight look to be already fairly developed, which one might expect given the later takeoff time for this flight. The cloud passes plotted and discussed below are presented by order of temperature, continuing progressively colder from the cloud base plotted above.
Note that this places some of the cloud passes out of sequential temporal order, as they are frequently not subsequent penetrations of the same cloud.

Figures 10-12 show sample CPI and 2D-S imagery, updraft and LWC time series, and Concentration PSDs, respectively, for a cloud pass at -0.5 °C into the middle of a growing turret (Fig. 9). This pass contains a moderate updraft of around 5 m s\(^{-1}\) near cloud edges and a 3 m s\(^{-1}\) downdraft in the middle. The LWC varies between 0.1 and 0.7 g m\(^{-3}\). The corresponding imagery and narrow size distributions show the pass is composed of all small drops, with an effective radius of only 8.25 µm.

**Figure 9.** Forward video screenshot from the Learjet. The red circle denotes the point of cloud entry for the pass at -0.5 °C presented in Figs 10-12.
Figure 10. Sample (left) CPI and (right) 2D-S10 from cloud pass at -0.5 °C showing small drops out to about 100-200 μm on the 2D-S.

Figure 11. Time series of (top) updraft velocity and (bottom) LWC.
Figure 12. (Top) Overlay and (bottom) composite of individual instrument PSDs at -0.5 °C showing population of small drops.
Observations for a re-penetration of the same turret at a similar level of -1 °C are shown in Figures 13-15. Figure 13 shows that while the CPI again observed all small drops, the 2D-S imagery shows small drops as well as rare drops out to 300-500 µm and large ice in the downdraft located near cloud edge, still resulting in a rather narrow size distribution shown in Figure 15. The updraft had weakened on this penetration, varying from 0-3 m s⁻¹. The LWC did not show much change from the first penetration, varying between 0.1-0.6 g m⁻³.

Figure 13. Sample (top) CPI, (bottom) 2D-S10 images from cloud pass at -1.5 °C showing small drops out to 50-70 µm with a rare 300-500 µm drop on the 2D-S. Some ice present in downdraft near cloud edge from 13:56:34-36.
Figure 14. Time series of (top) updraft velocity and (bottom) LWC.

Figure 15. (Left) Overlay and (Right) composite of individual instrument PSDs at -1.5 °C showing population of small drops with occasional larger drop.
Figures 16-19 show observations from penetration of a different turret (earlier in flight) at -4 °C. The cloud was penetrated right at cloud top (Fig. 16) and demonstrated a moderate downdraft (-3 to -5 m s⁻¹) with LWC varying from 0 to 1.25 g m⁻³, as plotted in Fig. 18. Cloud probe imagery from this pass, shown in Fig. 17, looks similar to the pass previously discussed at -0.5 °C, with all small drops and the occasional 100 µm drop.

Figure 16. Lear forward video showing -4 °C cloud penetration location (red circle) at cloud top.
Figure 17. Sample (left) CPI, (right) 2D-S10, and (bottom) Hawk-2D50 images from a cloud pass at -4 °C showing small drops with perhaps a rare 100 µm drop on the 2D-S and Hawk-2D50.
**Figure 18.** Time series of (top) updraft velocity and (bottom) LWC.

**Figure 19.** (Left) Overlay and (bottom) composite of individual instrument PSDs at -4 °C showing population of small drops with rare 100 µm drop.

Figures 20-23 show the next coldest penetration, at -5 °C, again of a different turret, but looking fairly similar to the previously discussed penetrations that showed all liquid. As seen in the imagery of Figure 21, this penetration was again composed of all small drops, with an occasional drop out to 300 µm. The vertical winds measurement again showed a persistent downdraft ranging from -1 to -7 m s⁻¹ and a LWC varying between 0.1 and 0.7 g m⁻³.
**Figure 20.** Lear forward video showing penetration location (red circle) of new turret at -5 °C.
Figure 21. Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images from cloud pass at -5 °C showing small drops with occasional 300 µm drop.

Figure 22. Time series of (top) updraft velocity showing consistent downdraft and (bottom) LWC.
Figure 23. (Top) Overlay and (bottom) composite of individual instrument PSDs at -5 °C showing population of small drops with occasional 300 µm drop.
A second penetration was made at -5 °C, this time descending into an alto-cumulus layer. As shown in the sample imagery of Figure 24, the particles of this pass were composed of again high concentrations of small drops, but interspersed with graupel, irregular ice, and rimed columns. Larger drops out to 400-500 µm were observed amongst the ice. These larger particles lead to a noticeable increase in concentration of particles with D > 100 µm in the size distributions plotted in Fig. 26 in comparison to previously discussed penetrations. There was no persistent updraft, with the vertical winds varying from -3 to +3 m s⁻¹ (Fig. 25). The LWC similarly varied from 0 to 0.7 g m⁻³.
Figure 24. Sample (top) CPI, (bottom) 2D-S10, and (bottom) Hawk-2D50 images from second cloud pass at -5 °C showing mostly small drops with a few drops out to about 300-500 µm, as well as a few aggregates and rimed columns on the CPI and interspersed throughout the 2D-S and Hawk2D-50 imagery.

Figure 25. Time series of (top) updraft velocity and (bottom) LWC.
Figure 26. (Top) Overlay and (bottom) composite of individual instrument PSDs from second cloud pass at -5°C.
The next coldest pass, at -6.5 °C, was made of two very closely spaced turrets, slightly off-center of the core, and thus composed of a continuous downdraft, varying between -2 and -6 m s⁻¹, and LWC between 0 and 1 g m⁻³, as shown in Fig. 28. The imagery for this pass, shown in Fig. 27, shows mostly small drops on the CPI and 2D-S, with the occasional 300-700 µm drop and a rare large ice particle, resulting in another fairly narrow particle size distribution, shown in Fig. 29.

Figure 27. Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images from cloud pass at -6.5 °C showing mostly small drops with an occasional 300-700 µm drop, and a rare larger ice particle.
A second pass was made at -6.5 °C through the same turrets, more directly through the middle of the clouds, with the observations plotted in Figs. 30-32. Since the updraft core was more squarely hit on this second pass of back-to-back turrets, the vertical winds time series, shown in Fig. 31, varied from +7 to -10, and back to +7 m s⁻¹, showing clearly the two updraft cores, with a downdraft in between,
though by this second pass the cloud had grown to fill the gap between the two updrafts, making for one continuous pass through cloud. The LWC on this pass was consistently around 1 g m⁻³ across the two updraft cores, falling to 0.2 g m⁻³ in between. The imagery, shown in Fig. 30, showed mostly smaller drops with an occasional 300–700 µm drop and a rare larger ice crystal. The resulting particle size distribution is slightly broader than observed in the warmer cloud passes discussed previously, though still fairly narrow, with a LWC < 1 g m⁻³, an effective radius of only 11 µm, and does not exhibit strong coalescence as might be observed in a cloud with a similar updraft and a warmer cloud base, thus giving a larger extent of warm cloud for the development of coalescence.
Figure 30. Sample (top) CPI, (middle) 2D-S10, and (bottom) 2D50 images from second cloud pass at -6.5 °C showing mostly small drops with an occasional 300-700 µm drop, and a rare larger ice particle.
Figure 31. Time series of (top) updraft velocity showing updraft at cloud edges and strong downdraft in middle of pass and (bottom) LWC.

Figure 32. (Top) Overlay and (bottom) composite of individual instrument PSDs from second cloud pass at -6.5 °C.

About twenty minutes prior to the two passes at -6.5 °C, the Learjet had made a penetration at -7.5 °C, just below cloud topo, as shown in Figs. 33-36. Figure 33 shows the location of entry just below the turret top, which was also just above the inversion level. The imagery for this pass again contained
lots of small particles in the CPI imagery, with the occasional 100 µm drop. The 2D-S10 and Hawk2D50 images (Fig. 34) also contained on occasional 300-500 µm drop and a few larger ice particles. This penetration was composed of a consistent downdraft (-3 to -7 m s\(^{-1}\)), and a LWC varying from 0.5 to 1.4 g m\(^{-3}\) (Fig. 35) The resulting composite size distribution shown in Fig. 36 is slightly broader than those previously discussed here, with a notable increase in the distribution above about 100 µm, which could perhaps be attributed to coalescence, though there are relatively few intermediate sized particles present in the imagery. Following the penetration, the Learjet made a turn to repenetrate the same turret, but sampling on this first pass had in fact blown the top out of the turret, leaving no cloud behind to sample.

**Figure 33.** Learjet forward video showing the turret sampled at -7.5 °C, and the point of entry denoted by the red circle.
Figure 34. Sample (top) CPI, (middle) 2D-S10, and (bottom) 2D50 images from cloud pass at -7.5 °C showing mostly small drops with an occasional 300-500 µm and some larger ice.

Figure 35. Time series of (top) updraft velocity showing a persistent downdraft and (bottom) LWC.
Figure 36. (Top) Overlay and (bottom) composite of individual instrument PSDs from cloud pass at -7.5 °C.
The coldest cloud penetration made on this science flight was at -11 °C, toward the edge of and into the mid-level of a turret growing up under a large extensive anvil outflow. The point of entry of the turret is shown in Figure 37. Not surprisingly, the CPI imagery (Fig. 38) is comprised of mostly small drops with a couple of ice particles with diameter 100-300 µm. The 2D-S10 imagery also contains mostly small drops with an occasional drop out to 300 µm, but not surprisingly also with the highest concentrations of ice seen in any penetrations thus far. The Hawk2D50 also contains some ice out to 3-4 mm, likely fallen from the anvil above. The vertical velocity of this updraft, plotted in Fig. 39, is highly variable, fluctuating between -4 and 3 m s⁻¹. The LWC is also variable, ranging from 0 to 0.4 g m⁻³. Correspondingly, the particle size distributions averaged across this pass is the broadest, given the population of mid-size drops and larger ice particles.

Figure 37. Learjet forward video showing entry of the coldest turret penetration during this science flight at -11 °C.
Figure 38. Sample (left) CPI, (right) 2D-S10, and (bottom) 2D50 images from cloud pass at -11 °C showing mostly small drops on the CPI and an occasional drop out to 300 µm on the 2D-S, with some ice out to 3-4 mm ice on the Hawk2D50.
Similarly to the convective clouds sampled on 12 and 13 August 2019, the convective clouds sampled on the 18 August 2019 UAE flight show moderate development and a weak coalescence process. Although strong updrafts (up to 7 m s⁻¹) were encountered on some penetrations of these
clouds, no strong coalescence was observed, and these clouds did not reach sufficient development to observe first ice development. Ice was observed in some of these clouds, likely fallen or mixed in from falling ice from nearby clouds. Development of these clouds was likely capped by the strong stable layer, and development may have been further influenced by entrainment of dry air. Sampling of convective clouds was again limited by location and air space, as many of these stronger convective clouds were out of reach beyond the Oman or Saudi borders, or else in restricted UAE airspace.
Analysis of aerosol-cloud interactions and their implications for precipitation formation using aircraft observations over the UAE:
Case studies of SF-1 (8-12-2019) and SF-4 (8-19-2019)

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Abstract
Aerosol and cloud microphysical measurements were collected by a research aircraft during August 2019 over the United Arab Emirates (UAE). The majority of science flights targeted summertime convection along the eastern Hajar mountains bordering Oman, while one flight sampled non-orographic clouds over the western UAE near the Saudi border. In this work, we study the evolution of growing cloud turrets from cloud base (9 °C) up to the capping inversion level (-12 °C) using coincident cloud particle imagery and particle size distributions from cloud cores under different forcing. Results demonstrate the active role of background dust and pollution as cloud condensation nuclei (CCN) with the onset of their deliquescence in the sub-cloud region. Sub-cloud aerosol sizes are shown to extend from submicron to 100 µm sizes, with higher concentrations of ultra-giant CCN (d>10 µm) from local sources closer to the Saudi border, compared to the eastern orographic region. Despite the presence of ultra-giant CCN from dust and pollution in both regions, an active coalescence process is not observed within the limited depths of warm cloud (<1000 m). The state-of-the-art observations presented in this paper can be used to initialize modeling case studies to study the influence of aerosol on cloud and precipitation processes in the region, and to better understand the impacts of hygroscopic cloud-seeding on these clouds.

1. Introduction
Aerosol particles are key components of the atmosphere and have multi-scale impacts on Earth’s climate and hydrological cycle, primarily through radiative transfer and precipitation formation. Aerosol effects are grouped into direct radiative effects [Ming et al., 2005] and indirect aerosol-cloud interactions [Lohmann et al., 2010]. The magnitude of uncertainty from indirect effects remains more difficult to quantify compared to direct effects [Solomon et al., 2007], given the complexity of the microphysical processes involved and their interdependencies [Morrison et al., 2005]. The contributions from thermodynamic and dynamic factors introduce further complexities to the precipitation generation process. Hence, assessing the impact of aerosols on cloud microphysics and precipitation generation has been a longstanding research area with many processes yet to be fully understood [Flossmann et al., 2019]. Our current knowledge is based primarily on observing the influence of background aerosols on the number and size distribution of hydrometeors [Hernández Pardo et al., 2019; Taylor et al., 2019; Wu et al., 2020]. Isolating these impacts has been shown to be particularly challenging in polluted and dusty environments. In such environments, the physicochemical properties of aerosols are continuously altered
between large dust particles, fine particle pollution and complex aggregates in response to both regional and local forcing [Abuelgasim and Farahat, 2020; Filioglou et al., 2020; Semeniuk et al., 2014].

The role of dust aerosols as ice nucleation particles (INPs) is well established through prolonging cloud lifetimes and enhancing precipitation in relatively unpolluted continental-tropical and maritime regimes [Koren et al., 2005; Y Liu et al., 2020]. Alternatively, when ingested into strong convective updrafts, large populations of mineral dust INPs tend to limit the growth of hydrometeors in the upper levels due to their competing effect for available water vapor [DeMott et al., 2003; Kant et al., 2019; Min et al., 2009; Sassen et al., 2003]. On the other hand, the role of dust as cloud condensation nuclei (CCN) in polluted desert environments with diverse aerosol physio-chemistry is less understood.

While dust introduces giant particles alluding to more effective collection during the collision-coalescence process, Rosenfeld et al. [2001] attributes the reduction in cloud droplet effective radii ($r_e < 14 \mu m$) over the Saharan desert to the presence of large concentrations of submicron CCN originating from desert mineral dust. This is shown to inhibit coalescence and warm rain formation, exacerbating a reduction in precipitation over the Sahara region. A similar conclusion is derived from the modeling studies of Flossmann and Wobrock [2010]. These findings contradict with previous work suggesting an enhanced coalescence process results from giant CCN regardless of the fine-mode concentrations [Johnson, 1982; Takeda and Kuba, 1982]. Aside from size and concentration, aerosol chemistry plays an important role in determining the nucleation properties of dust particles. Laboratory deliquescence experiments show that pure insoluble mineral dust particles remain hydrophobic at 100% relative humidity (RH), while the aggregation of dust particles with soluble compounds (e.g. NaCl) results in their deliquescence at 74% RH [Wise et al., 2007]. Similarly, compounds from anthropogenic pollution (sulfates) interact with mineral dust to produce internally-mixed aggregates which deliquesce at 80% RH [Semeniuk et al., 2015].

With less than 100 mm of annual rainfall (Wehbe et al., 2017), precipitation enhancement techniques such as cloud seeding (French et al., 2018; Vonnegut and Chessin, 1971) have been implemented within the UAE’s strategy to address water shortages in the region. This approach requires accurate understanding of local/regional meteorology, detailed characterization of the background aerosol particles and their efficiency to act as CCN/IN, and the complex interplay between aerosol-cloud-meteorology. Despite the Arabian Peninsula’s scarce rainfall and its regional contribution to both mineral dust and anthropogenic emissions, the UAE Unified Aerosol Experiment (UAEx) was the first and only comprehensive airborne assessment of aerosol characteristics in the Arabian Gulf [Reid et al., 2006]. The measurements indicated an abundance of sulfate-dominant fine-mode aerosols which may have strong implications for cloud and precipitation formation. Further evaluation of the impact of background aerosols as CCN/INP on cloud microphysics and precipitation was recommended as a high priority to refine operational cloud-seeding activities over the UAE [Almazroui and Farrah, 2017; Breed et al., 2007; Semeniuk et al., 2014]. To this end, here we use recently collected in situ aerosol and cloud microphysical measurements to assess the role of background aerosols on natural precipitation formation over the UAE. Representative measurements from two separate flight cases (August 12th and 19th, 2019) are used to study dominant eastern orographic convection along the Hajar mountains [Branch et al., 2020] and the less frequent southwestern convection associated with the Arabian heat low (AHL) [Steinhoff et al., 2018] near the Saudi border.
2. Regional Setting

Situated on the southeastern coast of the Arabian Peninsula, the UAE is impacted by both mesoscale sea-land breezes and microscale orographic storms with lifetimes less than 30 minutes. Interestingly, despite its minimal contribution to the country's annual rainfall average of 80–100 mm/year, the summer season records rainfall accumulations exceeding 100 mm over the eastern Hajar mountains bordering Oman [Wehbe et al., 2017; Wehbe et al., 2020]. In a recent study, Branch et al. [2020] calculated back-trajectories of summertime convective events over the eastern UAE by applying thermal radiance thresholds to the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Meteosat-7 and 10 retrievals during a 7-year period. While convection was found to be predominantly fostered along the Hajar mountain peaks (>80% of events) around 12:30 pm local time, a diurnal propagation of outflows toward the west was reported in the afternoon periods – coincident with the easterly sea breeze [Remiszewska et al., 2007].

On the other hand, Steinhoff et al. [2018] attributed the rare non-orographic summertime precipitation over the southwestern UAE to the increased activity of the southwest Asian monsoon trough over the northern Arabian Sea. This was shown to strengthen the circulation of the AHL, which shifted moisture transport in favor of deep convection initiation in the southwest desert inlands. Kumar and Suzuki [2019] also used Meteosat-10 retrievals for a satellite-based assessment of cloud climatology and seasonal variability of microphysical properties over the UAE. They reported a high occurrence of mixed-phase convective clouds along the coast and northeastern mountains during summer periods. Their analyses of cloud types showed higher warm cloud fractions over the mountainous regions, while cold cloud fractions were higher over the Arabian Gulf during winter and strictly localized along the Hajar mountains in summer. This is consistent with the radar-based analysis of Breed et al. [2007] which showed the highest frequency of mixed-phase clouds from orographic convection along the Hajar mountains during the summer months. Consequently, the August 2019 period was selected as the target period for the airborne campaign. A total of 11 science flights (SFs) sampled frequent orographic clouds west of the Hajar foothills, in addition to one set of non-orographic clouds over the southwest near the Saudi border. Figure 1 shows the flight tracks during the August 12th and 19th cases, referred to hereafter as SF1 and SF4, respectively, and the composite reflectivity from the UAE National Center of Meteorology (NCM) radar network.
3. Synoptic Situation and Thermodynamic Profiles

Figure 2a-d shows the synoptic situation using the European Centre for Medium Range Weather Forecasts Reanalysis 5 (ERA5) product [Hersbach and Dee, 2016] within 1-hour before each flight — at 11:00 and 12:00 UTC for SF1 and SF4, respectively. The mean sea-level pressure (MSLP) during SF1 (Figure 2a) shows the two typical pressure lows impacting the UAE during the summer season, namely, the Pakistan-India low [Bollasina and Nigam, 2011] and the Arabian Gulf low [Bitan and Sa'Aroni, 1992]. However, the SF4 case (Figure 2b) occurred during the less-frequent dominance of the AHL [Steinhoff et al., 2018] over the southwestern region. The low-level atmospheric thickness (LLAT) index is used for heat low detection (Figure 2c,d) as proposed by Lavaysse et al. [2009] for the West African heat low. The varying threshold (red color scale) is defined as 90\textsuperscript{th} percentile of the LLAT cumulative probability distribution function (i.e. the highest 10\% values of LLAT) computed from all the grid points (hourly scale used here). The active AHL extends from central Saudi Arabia to the southwest of the UAE during SF4 (Figure 2d).
Figure 2. MSLP (a,b) and LLAT (c,d) from ERA5 reanalysis and HYSPLIT back-trajectories (e,f) during SF1 and SF4 cases. Red back trajectories had lower altitude end points (1500 m) while blue back trajectories had end points at 4500 m. Different line styles are used to show back-trajectories to each of the three labeled end locations.
To further assess discrepancies between the two flight cases, air mass back-trajectories were computed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [Stein et al., 2015]. Figure 2e,f show the 1.5 and 4.5 km level back-trajectories to two locations within the flight area and a third control location to the south for each flight date. During SF1, all low-level (1.5 km) trajectories (Figure 2e) show the dominant sea breeze convergence inland and toward the Hajar foothills, while the upper-levels (4.5 km) indicate long-range westerly transport from the Indian regime. However, during SF4, more locally driven trajectories aligning with the extent of the AHL are observed over the Empty Quarter desert area to the west.

Figure 3 shows the Skew-T profiles derived for both flight dates comprised of aircraft temperature and dew point temperature measurements from the surface at 970 hPa (43 °C), to 400 hPa (-15 °C). Co-located ERA5 profiles (Figure 3a,b) and radiosonde observations (Figure 3c,d) from Abu Dhabi (AD) Airport (12:00 UTC) are overlaid for each case. Despite the different synoptic situation during the SF1 and SF4 cases, similar cloud base heights and temperatures of 3.5 km and 9 °C, respectively, are observed. These are typical values which fall within the long-term interquartile range of summertime convection (35-year analysis of AD Airport soundings, not shown). However, much drier conditions are evident in SF4 compared to SF1 soundings above the 700-hPa level. Although the ERA5 dataset provides high vertical resolution (~250 m), it fails to resolve the temperature inversions shown in the aircraft and AD Airport soundings. Strong upper-level temperature inversions at -13 °C and -12 °C are observed during SF1 and SF4, respectively. The large differences in the low-level dew point profiles between the aircraft and AD soundings is primarily due to the coastal location of the latter. The noise in the dew point temperature profiles between the 700 and 500 hPa levels indicates the aircrafts’ motion into and out of clouds.
Figure 3. Skew-T soundings from SF1 and SF4 descents (limited at 400 hPa level), co-located ERA5 grid points (a,b) and Abu Dhabi Airport (12:00 UTC) observations (c,d).
4. Data Set and Methods

4.1. Aircraft Instrumentation

The science flights were conducted by the Stratton Park Engineering Company (SPEC) Learjet 35A. The capability of the Learjet to conduct rapid maneuvers and swift ascents/descents was key for sampling the short-lived UAE clouds while complying with local air traffic restrictions. The aircraft was equipped with state-of-the-art cloud physics instrumentation used on multiple platforms throughout various airborne campaigns [R. Lawson et al., 2019]. The instruments deployed for the UAE campaign included a Condensation Particle Counter (CPC), Passive Cavity Aerosol Spectrometer Probe (PCASP), multiple optical array probes (OAPs) and scattering probes (see Table 1). Figure 4 shows the Learjet in-flight over Al Ain and selected instruments.

![Figure 4. Learjet in-flight over Al Ain and selected instruments: HVPS, FCDP, AIMMS and Hawkeye (from left to right)](image)

The scattering probes included a standalone Fast Cloud Droplet Probe (FCDP) [P. Lawson et al., 2017] and Fast Forward-scattering Spectrometer (FFSSP), with the latter upgraded to reduce the effects of ice shattering and processing lag time [O’Connor, 2008]. The scattering probes’ retrieval and processing mechanisms are provided in Knollenberg [1981] and in the Appendix of P. Lawson et al. [2017]. The instrument suite also included the Hawkeye [Woods et al., 2018], a recently developed composite system housing its own FCDP, two-dimensional stereo (2D-S) probe, and Cloud Particle Imager (CPI) [R. Lawson et al., 2001]. The CPI provides high resolution (2.3 μm) digital images of cloud particles for ice-phase habit identification [Woods et al., 2018]. The triple-coincident observations from the Hawkeye were especially useful for the mixed-phase clouds targeted in the UAE, where a size threshold was applied on the 2D-S as a trigger for the CPI to capture ice particle habits within a large population of
cloud drops. Only the CPI component of the Hawkeye was used in this paper, given the Hawkeye-FCDP measurements required further calibration and testing.

The OAPs included a total of three 2D-S probes (two standalone and one within the aforementioned Hawkeye) and one High Volume Precipitation Spectrometer (HVPS) described in [R P Lawson et al., 2006] and [R Lawson et al., 1993a; R P Lawson et al., 1993b], respectively. A total of five channels (three vertical and two horizontal) provided redundant measurements at 10 µm resolution (see Table 1) which served for data quality control (see Table 1). Post-processing of the OAP imagery involved noise filtering and corrections for particle overlapping and ice shattering as outlined in R Lawson [2011]. Size estimates from the both the M4 and M7 approach described in P Lawson et al. [2017] were used for smaller (round drops) and larger (irregular ice) shapes, respectively.

As listed in Table 1, cloud droplet size distributions were derived using the well-established FFSSP and 2D-S instruments, while the usage of the standalone FCDP was limited to coarse mode aerosol measurements to complement the PCASP accumulation mode measurements. The fine-mode PCASP measurements were quality controlled by adjusting the sample volume to account for pressure-induced pump rate lags, especially at altitudes exceeding 4.5 km. The first two size bins (0.1–0.12 µm) were also excluded from the total concentration calculations to avoid data contamination from excessive noise. All PCASP total concentrations were filtered for out-of-cloud measurements by applying dual thresholds on the FSSP total number concentration (20 cm⁻³) and hot-wire LWC of (0.01 g.m⁻³), above which is considered a cloud pass [Alexei Korolev and Isaac, 2006]. Similar to a CCN counter, but forced with higher supersaturation, the CPC provided counts of ultra-fine mode aerosols (0.01–3 µm) through deliberate water-based condensation of intercepted particles to reach sizes detectable by a laser counter [W Liu et al., 2006; Wang et al., 2015]. Finally, an Aventech Model Aircraft Integrated Meteorological Measurement System (AIMMS) logged 1-Hz basic meteorological variables and air motion measurements [Beswick et al., 2008], while a Nevzorov hot-wire probe [AV Korolev et al., 1998] measured the total and liquid water contents (LWC) – used here as the reference value compared to LWCS registered by the scattering probes and OAPs.
Table 1. List of instruments used for the collection of measurements used herein.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Purpose</th>
<th>Size range</th>
<th>Used here</th>
</tr>
</thead>
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<td>PCASP</td>
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<tr>
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<td>✓</td>
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<tr>
<td>HVPS</td>
<td>Precipitation particle shapes and spectra</td>
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<tr>
<td>AIMMS</td>
<td>Basic meteorological variables</td>
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</table>

(1) 10HV indicates 10 µm resolution in both the horizontal (H) and vertical (V) channels.
(1) 50H indicates 50 µm resolution in the horizontal (H) channel.

4.2. Cloud penetration selection and classification

A total of 13 and 22 cloud penetrations were conducted during SF1 and SF4, respectively. Here, the analysis is primarily focused on penetrations from growing turrets, aiming to sample representative cloud conditions. Penetrations from precipitating and decaying clouds are not considered, with the exception of one penetration during SF1 (used for illustration). The growing turret measurement intervals are identified based on the hot-wire LWC and updraft velocity thresholds of 0.5 g.m⁻³ and 3 m.s⁻¹, respectively, and verified by in-flight video footage from the aircraft cockpit.

To minimize data contamination from entrainment and evaporation effects or artificial spikes in the 1-Hz acquisitions, only measurements from cloud cores are extracted. Avoiding entrainment effects is particularly challenging in this region’s dry environment where even the most undiluted penetrations are contaminated by downdrafts. The analyzed cloud cores were sub-adiabatic in all cases. The Steady State (SS) and Maximum Drop Concentration (MDC) methods proposed by Tessendorf et al. [2013] are used to manually identify the most isolated cloud core measurements within each penetration time series. Both methods are used to identify the undiluted core and better attribute the measured spectra to the sub-cloud aerosol. As the name suggests, the SS method is based on the assumption that LWC
and droplet concentrations remain relatively constant during a 3-second window, while the MDC method averages the measurements over the 3-second window of maximum concentrations to better correlate with sub-cloud aerosols measurements. Both methods are applied by manual inspection of the time series data. We first present the background aerosol analysis, followed by a detailed microphysical analysis and inter-comparison between the two.

5. Results and discussion

5.1. Aerosol Measurements

Figure 5 shows the 3D flight tracks from both cases and their PCASP total concentrations measurements throughout. All flight ascents are southward out of Al Ain, climbing to around 6 km and penetrating clouds on the descent over the southwest and Al Ain during SF1 and SF4, respectively. For both flight cases, the PCASP concentrations on the ascent show a 10-fold increase compared to those of the descent over Al Ain, even at low altitudes (below 1500 m). This can be explained by multiple co-occurring effects. The convective outflow from the Hajar mountains toward Al Ain and the coincident timing of the SF1 descent with the peak in diurnal sea breeze activity (around 12:00 UTC) [Eck et al., 2008] can form a convergence zone over the region of Al Ain which is subject to orographic trapping of dust along the Hajar foothills [Schwitalla et al., 2020]. The effect of the orographic dust trapping is evident from the higher PCASP descent concentrations from SF1, which is further east toward the Hajar ridge, compared to that of SF4 with a direct descent over Al Ain (see Figure 1). Also, the ascent-descent magnitude split in the PCASP profiles are less pronounced for flights on non-cloud (dry) days (i.e. SF5 and SF9 – not shown here). This indicates the strong contribution from the outflow of convection and thunderstorms during cloudy days (SF1 and SF4) coupled with the prevalent dust-laden haboob winds [Miller et al., 2008]. The range of penetrated cloud temperatures are shown for each flight, with high concentrations of around 1000 cm⁻³ at cloud base (9 °C) in both cases.
Figure 5. 3D flight track of SF1 and SF4 with PCASP total number concentrations (cm$^{-3}$). SF1 penetrations over Al Ain from cloud tops at $-13$ °C down to 9 °C bases (a), and SF4 penetrations over the southwest from cloud tops at $-12$ °C down to 9 °C bases (b) are shown.

The vertical profiles of PCASP total number concentrations are shown in Figure 6. During the SF1 ascent, the concentrations decrease from around 400 cm$^{-3}$ to 100 cm$^{-3}$ within the boundary layer up to 2 km, and increase again to 180 cm$^{-3}$ around 4 km. Additional variations in the change in aerosol concentration with altitude are observed up to the top 7 km level, while the descent shows relatively less variability. This suggests the presence of multiple dust layers (labeled L1-4 on Figure 6a) on the cloud-free ascent and more mixed conditions with higher concentrations are observed on the descent with cloud development. A well-mixed profile is observed on both the ascents and descents of SF4 as clouds were
present over the southwest and Al Ain, but the magnitude split is still evident between the two profiles. The observed stratification of dust layers is in line with the ground-based Lidar observations from Filioglou et al. [2020] over Al Dhaid – situated along the Hajar foothills at 130 km from Al Ain – where they report four separate layers up to 6 km during August 2018. The dust layer stratification is imposed by gravitational waves produced from the sea breeze-mountain overpasses during the afternoon period and by multiple temperature inversions (see Figure 3) which are frequently observed during the summer months [Weston et al., 2020].

Figure 6. Altitude profiles of out-of-cloud PCASP total number concentrations for SF1 (a) and SF4 (b). L1-4 designate multiple dust layers at levels of significant change in concentration gradients. The profiles are computed as the best-fit from shape-preserving spline interpolation [Kvasov, 2000] of the full 1-Hz dataset.

The time series of altitude (and temperature) for SF1 and SF4 are shown in Figures 7a and 7c, respectively. Cloud bases are sampled at around 3 km and 9 °C in both cases. The selected time series of the sub-cloud and in-cloud LWC (hot-wire), PCASP and FFSSP total number concentrations are displayed in Figures 7b and 7d. Coincident peaks in the LWC and FFSSP total concentrations indicate a cloud base penetration, while intermediate intervals are considered sub-cloud measurements. In both cases, the mean sub-cloud PCASP total number concentrations vary around 500 cm\(^3\), but with higher variations (up to 1000 cm\(^3\)) during SF1. The mean background total concentration of 500 cm\(^3\) is in close agreement with those recorded over the Sahara desert by Rosenfeld et al. [2001]. On the other hand, the LWC shows excessive noise during the SF4 sub-cloud passes with peaks of around 0.2 g.m\(^{-3}\) compared to SF1 (<0.05 g.m\(^{-3}\)), which may be attributed to the hot-wire response to heavy dust (and
haze) loading from local pollution over the southwest. This is corroborated by the more frequent FFSPP measurements during SF4 compared to SF1, suggesting the presence of large background aerosols from local pollution and dust. The CPC concentrations closely match those recorded by the PCASP during SF4 (the CPC was not operational during SF1). This indicates the hygroscopic nature of the ultra-fine background aerosols over the southwest, which is consistent with the experimental results of Semeniuk et al. [2015].
Figure 7. Time series of PCASP, FFSSP and CPC total number concentrations and hot-wire LWC for sub-cloud intervals during SF1 over Al Ain (a) and SF4 over the southwest (b).
Figure 8 shows the background aerosol size spectra from SF1 and SF4 merged from overlaps between the PCASP, FCDP, FFSSP and 2D-S10 measurements. A higher concentration of fine-mode aerosols between 0.1–0.2 μm is observed during SF1 compared to SF4 with a peak difference of approximately 5×10^5 L⁻¹ µm⁻³. Alternatively, higher tail concentrations from ultra-giant sizes of 20–50 μm are recorded during SF4 compared to SF1. This is in line with the previous suggestion of higher ultra-giant CCN loading from local pollution and dust aggregation over the southwest compared to the eastern regime.

Figure 8. Mean sub-cloud aerosol size distributions for during SF1 (Al Ain) and SF4 (southwest).

5.2. Cloud Microphysics

The SS and MDC methods gave matching instances for the most undiluted cloud core measurements (closest to adiabatic cores) with adiabatic fractions between 0.6–0.8. Figure 9 shows the coincident imagery from the 2D-S10, Hawkeye-CPI and cockpit camera at multiple levels of growing turrets sampled during SF1. The altitude, temperature, vertical velocity range, hot-wire LWC, FFSSP total number concentration and median volume diameter (MVD) are listed in Table 2 for each level. The FFSSP and FCDP (not listed) concentrations just above cloud base (9.1 °C) are comparable at 800 and 1144 cm³, respectively. The maximum LWC of 0.8 g.m⁻³ is coincident with the peak updraft velocity of 3.1 m.s⁻¹ and an 8.7 μm MVD. At the next level (4.5 °C), slightly lower FSSP (621 cm⁻³) and higher FCDP
(1598 cm\(^{-3}\)) concentrations are recorded with a stronger updraft (6.9 m.s\(^{-1}\)) and higher LWC (1.2 g.m\(^{-3}\)) compared to the previous level. This difference suggests that more than 50\% of the intercepted hydrometeors are within the medium size range (d < 6 \(\mu\)m) which are better captured by the FCDP. Similar values are also observed at the 3.2 \(^{\circ}\)C level with a comparable updraft (6.2 m.s\(^{-1}\)) and LWC (1.2 g.m\(^{-3}\)). The 2D-S10 and CPI imagery for the lowest three levels (Figure 9c–e) confirm the dominance of small drops (d < 10 \(\mu\)m) with the exception of a couple of large drops (~150 \(\mu\)m) captured by the 2D-S10. This is consistent with the calculated MVD values ranging from 8.9 to 10.9 \(\mu\)m from the three warm levels.

In terms of ice processes in the upper portion, ice is observed by the CPI and 2D-S10 at the -11.9 \(^{\circ}\)C level, showing very few ice particles with a habit of sector plates, as expected by nucleation at -12 C at relatively high liquid water contents of 1.1 g.m\(^{-3}\) [Pruppacher and Klett, 1980]. This observation is within a decaying turret (-12.4 m.s\(^{-1}\) peak downdraft). Interestingly, at the highest sampled level (-12.6 \(^{\circ}\)C) of a growing pileus cloud, a dominant population of liquid drops (d<50 \(\mu\)m) are observed in the absence of ice particles with a LWC of 1.4 g.m\(^{-3}\) and a strong 17.8 m.s\(^{-1}\) updraft. The calculated MVDs remain less than 20 \(\mu\)m in both of these subzero temperature penetrations.

Table 2. Penetration altitude, temperature (T), vertical velocity range (Vv), FFSSP total number concentration (N-FFSSP) and MVD values from SF1 and SF4 (see Figures 8 and 9).

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>T ((^{\circ})C)</th>
<th>Vv (m.s(^{-1}))</th>
<th>LWC (g.m(^{-3}))</th>
<th>N-FFSSP (cm(^{-3}))</th>
<th>MVD ((\mu)m)</th>
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<tr>
<td>7040</td>
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<tr>
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<td>619</td>
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<tr>
<td>SF4 penetration levels (Figure 10a-f)</td>
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<td>778</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>541</td>
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Following the same format of Figure 9, the growing cloud turret penetrations at multiple levels during SF4 are shown in Figure 10. At cloud base (8.6°C), comparable concentrations from the FFSSP (541 cm⁻³) and FCDP (605 cm⁻³) are recorded at the peak 3.2 m.s⁻¹ updraft and 0.2 g.m⁻³ LWC. The CPI and 2D-S10 capture a few 100 µm drops which appear to be deliquesced dust and pollution aggregates, as suggested from Figure 7b. At the next slightly colder cloud base (8.3°C), more 100 µm drops are captured by the CPI with higher total concentrations and LWC of 0.7 g.m⁻³ which further corroborates the deliquescence of background aerosols with increasing relative humidity. However, at the next -0.3 °C and -3.5°C levels, small drops (d<50 µm) dominate the imagery similar to SF1. Additionally, the LWC remains high (1.2–1.3 g.m⁻³) for the upper subzero levels where graupel and ice irregulars (0.5–1 mm) are detected at -10.3 and -11.7 °C. The strong updraft (24.4 m.s⁻¹) may have carried a limited number of large particles aloft to serve as ice nuclei at the -11.7 °C level.
Figure 10. Same as Figure 9 but for SF4. Measurements from each penetration level are listed in Table 2.

To intercompare the evolution of droplet sizes with altitude, Figure 11 shows the merged size spectra from the PCASP, FFSSP, 2D-S50 and HVPS measurements during SF1 (a) and SF4 (b) at the levels presented in Figures 9 and 10, respectively. For the SF1 9.1°C level, a peak concentration of $10^5$ L$^{-1}$ µm$^{-1}$ is shown for the sizes between 6–10 µm, which is consistent with the imagery-based analysis (Figure 9e). For sizes larger than 10 µm, the concentrations drastically decrease to around 10 L$^{-1}$ µm$^{-3}$, while the 2D-S50 shows sizes up to 200 µm sizes at minimal concentrations of $10^3$ L$^{-1}$ µm$^{-1}$. At the next two 4.5°C and 3.2°C levels, no broadening is observed with a similar decrease in concentrations for sizes larger than 10 µm. Similarly, the cloud base penetration of SF4 at 8.6 °C reveals a consistent peak in the concentrations of 6–10 µm sizes, followed by a sharp decrease in concentrations thereafter. However, the 8.3 °C and -0.3 °C levels show slight broadening with the peaks extending to 20 µm, which corroborates the suspected hygroscopic characteristics of the southwest ultra-fine background aerosols (see Figure 7b). Rosenfeld and Gutman [1994] report an effective radius larger than 14 µm needed to trigger coalescence and warm rain generation, which is in line with other works [Benguier and Chaumat, 2001]. Furthermore, Pinsky et al. [2001] reports a 3% collision efficiency between collector and collected drops of 60 µm and 10 µm sizes, respectively, while the efficiency increases to 45% for collisions with collected drops of 25 µm sizes. Consequently, the concentration of intermediate sizes (15–30 µm) should be at
least one order of magnitude larger than any other size range for an efficient coalescence process. Given the dominance of small-sized particles with diameters less than 10 µm and the minimal concentrations of intermediate sizes (10–30 µm) from measurements during both flights, an active coalescence process is not achieved. A further inhibiting factor is the limited depth of warm cloud (<1000 m) which is critical for the development of coalescence [Johnson, 1993].

Figure 11. Size distributions at multiple temperature levels of growing turrets from the PCASP (dashed), FFSSP (solid), 2D-S50 (dashed) and HVPS (solid with circle markers) measurements during SF1 (a) and SF4 (b).

For the subzero cloud levels of SF1, the broadening of the decaying turret (-12.4 °C) is primarily attributed to fallout ice (see Figure 9b) with sizes extending to the millimeter scale. However, for the growing turret at -12.6 °C with a pure liquid phase, the broadening may be attributed to the growth of a limited number of super-cooled liquid drops with concentrations as low as \(10^5 \text{ L}^{-1} \text{ µm}^{-1}\). Dust aerosols, acting as ice nuclei, do not appear to be transported to this level, which agrees with the observations of Filioglou et al. [2020] close to the Hajar foothills. For the SF4 subzero levels, broadening is observed for sizes larger than 100 µm extending up to mm-sized irregulars and graupel at -11.7 °C, but at low concentrations within a dominant population of small liquid drops (see Figure 10a and b). Unlike the case of SF1, dust and pollution aggregates appear to have served as INPs given the strong updrafts (24.4 m.s\(^{-1}\)) at the coldest level of SF4.

Several studies are in agreement that ultra-giant nuclei (d>40 µm) may serve as precipitation embryos when their concentration is larger than 30 m\(^3\) [Bartlett, 1970]. The potential sources of such nuclei can be large CCN, sulfate-dominant mineral dust [Wurzler et al., 2000], or simply water insoluble particles serving as coalescence embryos [Lasher-Trapp, 1998]. The work of Hoose and Möhler [2012] suggests that dust particles may form into ice particles at T<15°C. However, they may act as INPs at even higher temperatures depending on their chemical composition, size and concentration [Harrison et al., 2016; Peckhaus et al., 2016]. Reasonable K-feldspar fractions were reported by Kaufmann et al. [2016] from
samples collected over Qatar, while no traces were observed in samples from Oman. This may explain
the formation of ice irregulars at the subzero levels of SF4 over the southwest near Qatar, given the ice-
nucleating properties of K-feldspar.

5.3. Implications for Hygroscopic Cloud-Seeding

The general concept of hygroscopic seeding is based on the notion of introducing large artificial
(hygroscopic) particles to suppress the depletion of cloud liquid water by smaller naturally occurring
aerosols. By inhibiting this so-called “competition effect”, the larger particles are expected to rapidly
grow into large drops and trigger the collision-coalescence process [Bruintjes et al., 2012; Cooper et al.,
1997]. Hence, the characteristics of the background aerosol population, namely their size, concentration
and chemical composition are considered key precursory properties to determine, and potentially
improve, the effectiveness of seeding. Hygroscopic seeding is conducted operationally in several
countries and has been actively implemented over the UAE for the past three decades.

The measurements and analysis provided in this study have important implications for operational
seeding activities over the UAE. Our results indicate that relatively large aerosols sizes are already
present in the UAE environment – over both the eastern and southwestern region – with comparable
sizes to typical hygroscopic flare particles (d<10 µm). Furthermore, the ambient aerosols appear to be
hygroscopic in nature with their deliquescence and growth to peak concentrations of 20 µm sizes above
cloud base. This is more pronounced over the southwestern region where mineral aggregates are
formed from sea salt and sulfate particles emitted from local oil refineries [Semeniuk et al., 2015].
However, the collision-coalescence process remained inactive in all observed cases. It is hypothesized
that a strong competition effect persists due to the high concentrations of fine-mode aerosols, which
prevent broadening of the droplet spectra. Given the comparable sizes between the ambient and typical
seeding aerosols, it is unclear if hygroscopic seeding can be effective in these clouds. Modeling studies
are needed to help assess the potential effectiveness of perhaps larger seeding aerosol sizes (10–15 µm)
in suppressing the competition effect and initiating collision-coalescence.

6. Conclusion

According to the most recent review on precipitation enhancement research by the World
Meteorological Organization (WMO) Expert Team on Weather Modification, a more reliable assessment
of the aerosol-cloud-precipitation interaction is needed, particularly using in-situ aircraft observations
that can validate model results [Flossmann et al., 2019]. Located in a regional dust hotspot impacted by
air masses originating from five subcontinents over its coastal (west) and mountainous (east)
topography, the UAE is considered a “natural laboratory” to study both mesoscale (e.g. sea-air
integration) and microscale (aerosol-precipitation) processes within a limited geographical area,
representative of the larger understudied Arabian Peninsula environment.
Here, we present aerosol and cloud microphysical measurements from research flights during August 2019 over two distinct convective regimes of the UAE – orographic convection over the Hajar mountains bordering Oman and non-orographic convection over the southwestern Saudi border. Sub-cloud aerosol sizes are shown to extend from 10 nm up to 100 µm sizes, with higher concentrations of larger sizes, associated with anthropogenic pollution over the southwest, acting as ultra-giant CCN. The maximum sizes are approximately double those observed over the Sahara desert [Weinzierl et al., 2009]. Despite the existence of ultra-giant CCN, no indications of a natural collision-coalescence process are observed. It is suggested that the low concentration of ambient intermediate aerosol sizes (10–15 µm) may explain the inactivation of collision-coalescence, in addition to the limited depth (<1000 m) of the warm portion of the cloud [Johnson, 1993]. The results have key implications for ongoing operational cloud-seeding activities over the UAE, which rely on hygroscopic material of less than 10 µm sizes. Modeling studies are needed to further assess the influence of aerosol on clouds and precipitation in these clouds, as well as to study implications for hygroscopic cloud-seeding in the UAE. Model simulations can be initialized from the observations provided in this paper to assess the sensitivity of different seeding strategies to enhance rainfall over this water-stressed region.

Acknowledgement

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The Final Summary Budget with break down for each year (PI/Co-PIs, Faculty Personnel Wages)

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The detailed description to date will be used for publications that are in progress.

Expenditures: $61,787.30 - $399,320.44 - $60,854.10 - $762,065.98 - $1,222,240.52 = $1,249,634.00.