THE QUEENSLAND CLOUD SEEDING RESEARCH PROGRAM

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An innovative approach to studying the effects of cloud seeding on precipitation is to focus on understanding the natural variability of precipitation and the microphysical responses to aerosol.

For much of the last decade, most of eastern and southern Australia was under severe drought conditions due to mounting rainfall deficiencies. The Bureau of Meteorology (2011) reported that the lack of late winter and spring rains in 2006 made matters worse; in fact, that period was the third driest August–November period across Australia based on the historical record dating from 1900. Needless to say, the availability of water became a community concern, such that water restrictions were commonplace and conservation programs became a top priority. Plans to build desalination plants in all the major coastal cities of Australia were enacted. In addition, cloud seeding was considered by a number of communities. Australia has a long history of cloud seeding (Kraus and Squires 1947; Smith et al. 1963, 1979; Warburton and Wetzel 1992; Ryan and King 1997; Huggins et al. 2008; Morrison et al. 2009, 2010), although most of these efforts have been focused on glaciogenic seeding techniques (using silver iodide) over the mountains in southeastern Australia and Tasmania.

In late 2006 the Queensland government decided to establish the Queensland Cloud Seeding Research Program (QCSRP) in southeastern Queensland (Fig. 1) to determine

Fig. 1. Map of southeast Queensland region targeted for the QCSRP field effort and associated facilities and landmarks. The 30° beam crossing angle dual-Doppler lobes are overlaid in black. [Courtesy of Kevin Sampson, NCAR.]

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the feasibility of cloud seeding as a component of its long-term water management strategy. The Queensland water management strategy recognizes the need for a broad portfolio of water sources to account for the uncertainties and costs associated with each type of source. While it was not expected that cloud seeding would restore southeastern Queensland's water supply levels to predrought values, it seemed valuable to determine whether certain types of seeding techniques might impact rainfall and water supplies in the region and whether that impact could be quantified. The project was developed as a collaboration between a number of institutions from Australia, the United States, and South Africa, and included field measurements over the course of two wet seasons. A two-pronged approach was taken to a) conduct a randomized cloud seeding experiment and b) assemble state-of-the-art instrumentation systems to collect data on the complete physical process from cloud formation to seeding to precipitation.

Meanwhile, in stark contrast to the drought and since the conclusion of the QCSRP, the state of Queensland has undergone a dramatic climatic shift, having had several rainy seasons and recently having been inundated by catastrophic flooding. While this did not affect the purpose and need for the QCSRP at the time, it is pertinent to point out that the dramatic climate changes this region of the world is undergoing has an extraordinary impact on the communities in the region, and thus developing methods to mitigate these impacts is crucial to the sustainability of these communities.

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EXPERIMENTAL STRATEGY.

The conceptual model of hygroscopic seeding is based on the principle that if you can enhance the collision and coalescence process, then it will yield more rainfall at the ground, thereby improving the precipitation efficiency of a cloud [for more background, see reviews by Cotton (1982), Bruintjes (1999), and Cotton (2009)]. Thus, clouds are seeded with hygroscopic materials (particles that take on water easily, such as salts) in the updraft region of the cloud just below the cloud base. These particles are then carried into the cloud by the updraft where water vapor condenses on them to form additional liquid cloud droplets, whose size depends on the size of the hygroscopic particles introduced into the cloud. Adding hygroscopic particles of larger sizes should help enhance collision and coalescence processes and convert more of the cloud water to rainfall.

There are many complicating factors, however, behind trying to assess the impact of hygroscopic cloud seeding, or even pollution aerosols, on clouds and ultimately on rainfall. In the atmosphere, we do not have control cases as one would create in a lab setting, and thus such atmospheric experiments always fall short of being able to isolate causality of such aerosol effects. Statistical analysis has often been used in cloud seeding assessment studies (e.g., Mather et al. 1997; Bruintjes 1999; Silverman 2003), in which clouds are seeded (or not) based on a set of predetermined randomized decision cards. Once the seeding aircraft finds a cloud that meets a set of basic criteria for the randomized experiment, a case is declared, the next sequential randomized decision card is opened, and the cloud is then either seeded (or not) based on the predetermined action. The criteria used in the QCSRP randomized experiment to select a cloud was that a cloud needed to have a rain-free cloud base at least 2 km in diameter, with an updraft that was detectable by the pilot of roughly 2 m s^{-1} or greater. This builds up a sample of cases that ideally are all similar in nature, with roughly half having been seeded, and statistical tests can be performed on various characteristics of the observed cells. These characteristics, such as precipitation flux, rain mass,

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and storm duration, are traditionally derived from single-polarization[1] radar echoes of the randomized cases.[2] However, this statistical approach is usually limited by the number of randomized cases that can be declared and measured by radar (and/or aircraft) for a given limited time frame experiment as well as by the lack of physical observations to substantiate and explain any statistical relationships that may be found. Furthermore, in regions with considerable natural variability, it is even more challenging to obtain a large enough sample to achieve statistical significance because of the underlying "noise" that results from that variability.

a) b)

Fig. 2. Facilities operated during the QCSRP included (a) the CP2 radar (photo depicts the S-band and X-band antennae), and (b) the SAWS Aero Commander research/seeding aircraft depicted in flight on a research mission. [Photos courtesy Scott Collis, CAWCR.]

For the first objective of our two-pronged approach in the QCSRP, we conducted a traditional randomized cloud seeding experiment (Mather et al. 1997). Over the course of two seasons, we performed randomized cloud seeding in 127 clouds and then a statistical analysis was performed using single-polarization, radar-derived quantities to characterize the rainfall and behavior of each randomized cloud. Despite collecting that reasonable sample of randomized cases, a major obstacle in the statistical analysis of randomized seeding datasets is the effect of initial biases and outliers (large storms) in addition to the effects of merging and splitting cells that can complicate the radar-based analysis. Thus, after accounting for these factors, only 39 of the 127 randomized cases were able to be included in the statistical analysis, which was too small of a sample to gain statistical significance among the natural variability in the sample (Tessendorf et al. 2010). Without the predictive ability to only target those clouds that will produce radar echoes, but not merge and become outliers, these issues will always be limiting factors in getting a large enough sample of cases in randomized seeding statistical experiments. This is especially true in regions with great natural variability, such as in the coastal region of southeast Queensland. Thus, the rationale for using physical measurements to first understand the natural variability, perhaps even prior to conducting a randomized seeding experiment, has been an important outcome from this program.

For the second objective of our two-pronged approach, we focused on gaining a *physical* understanding of the effects of both ambient aerosols and seeding material on precipitation formation in southeast Queensland clouds. To meet this goal, the QCSRP employed a unique observational infrastructure compared to past cloud seeding experiments. In the region of interest, the Australian Bureau of Meteorology (BOM) operates a dual-wavelength (S and X bands), dual-polarization Doppler radar (CP2;[3] Fig. 2a) as well as an operational Doppler radar (Mt Stapylton) and other operational weather radars. The QCSRP operational domain was focused in this region near Brisbane, Australia, around the location of the CP2 research radar, and also utilized the nearby Marburg and Mt Stapylton BOM operational radars (Fig. 1). The combination of the CP2 and Mt Stapylton Doppler radars also provided dual-Doppler

[1] Such methods for calculating rainfall quantities for randomized experiments can be misleading since single-polarization radars assume a constant drop size distribution when calculating rainfall quantities, and seeding may be altering the size distribution. Dual-polarization radars have promise, in that they infer drop size and yield improved rainfall estimates; however, methodologies to utilize such dual-polarization measurements in the statistical analysis are not fully developed.

[2] Tracking software, such as Thunderstorm Identification, Tracking, Analysis, and Nowcasting (TITAN; Dixon and Wiener 1993), is often used to objectively track the echoes.

[3] CP2 was acquired by the BOM in 2006 from the National Center for Atmospheric Research (NCAR; Keenan et al. 2007). Characteristics of the radar are presented in Bringi and Hendry (1990) and Keenan et al. (2007).

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radar analysis capabilities (see Fig. 1). The use of multiparameter radar in the QCSRP provided for the first time the ability to study cloud seeding with innovative remote sensing observations. The field phase of the project also incorporated an instrumented research aircraft and a cloud seeding aircraft: the South African Weather Service (SAWS) Aero Commander was the primary research aircraft, but it also served as a secondary seeding aircraft if conditions warranted;[4] and the Weather Modification, Inc. (WMI) Piper Cheyenne II was the primary seeding aircraft. The SAWS Aero Commander (Fig. 2b) carried flare racks on each wing (10 burn-in-place flare capacity each), and it had a full suite of atmospheric instrumentation capable of taking aerosol and microphysical measurements in seeded and unseeded clouds, described in Table 1. Novel instruments for cloud seeding research included the differential mobility analyzer (DMA) for measuring the fine-mode range of aerosol particle sizes and an aerosol impact sampler for assessing particle composition, in addition to the normal suite of aerosol and cloud physics probes. Figure 3 illustrates the region around Brisbane in which airborne seeding and research operations were conducted.

The measurements collected in the QCSRP are being used for a variety of analysis objectives[5] aimed at assessing the impacts of both ambient aerosol and cloud seeding particles on rain formation. The overarching goals of the QCSRP are to 1) determine the characteristics of local cloud systems (i.e., weather and climate, 2) document the properties of atmospheric aerosol and their microphysical effects on

[4] In season 2, only the SAWS research aircraft was available and thus also served as the seeding aircraft.

[5] Additional details on the QCSRP experimental strategy and objectives are discussed in Tessendorf et al. (2010).

Table 1. List of cloud physics and aerosol instrumentation on the SAWS Aero Commander in each season of the QCSRP. PMS = Particle Measuring Systems; DMT = Droplet Measurement Technologies; FSSP = Forward Scattering Spectrometer Probe; CAPS = Cloud, Aerosol, and Precipitation Spectrometer.

Instrument	Purpose/comment	Range	Season
Cloud physics			
PMS FSSP	Cloud droplet spectra	3–47 μm	1
DMT SPP-100 FSSP	Cloud droplet spectra	3–47 μm	Both
PMS 2D-C	Small precipitation particle size, concentration, and shape	25–800 μm	1
PMS 2D-P	Large precipitation particle size, concentration, and shape	200–6,400 μm	1
DMT Cloud Imaging Probe (CIP)	Small precipitation particle size, concentration, and shape (part of CAPS probe listed below)	25–1,550 μm	Both
DMT Precipitation Imaging Probe (PIP)	Large precipitation particle size, concentration, and shape	100–6,200 μm	2
PMS Hot-Wire (King) Liquid Water Content (LWC) Probe	LWC	0.01–3 g m^{-3}	Both
DMT CAPS probe	Aerosol through precipitation size spectrometer; LWC; CIP; static and dynamic pressure; temperature	Multiple	Both
Aerosols			
DMT CCN Counter	CCN concentration	Depends on supersaturation	Both
DMA	Fine-mode aerosol concentration, spectra	0.01– 0.38 μm	Both
PCASP	Aerosol concentration, spectra	0.1– 3 μm	1
DMT SPP-200 PCASP	Aerosol concentration, spectra	0.1– 3 μm	2
Aerosol particle impact sampler	Aerosol chemical composition	N/A	Both

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precipitation formation, and 3) assess the impact of cloud seeding on cloud microphysical and dynamical processes to enhance rainfall. During the course of the field program, it became clear that there is great variability in the natural cloud systems in the southeast Queensland region, and understanding that variability would be necessary before any conclusions could be made regarding the impact of cloud seeding. This article presents research highlights and progress toward achieving the goals of the program, along with the challenges associated with conducting cloud seeding research experiments.

LOCAL ENVIRONMENTAL CHARACTERISTICS AND AEROSOL PROPERTIES. The climatology of weather, especially pertaining to rainfall, in southeast Queensland has been characterized (see Tessendorf et al. 2010) and can generally be divided into "wet" and "dry" regimes. The wet regimes occur during the austral summer months of November–February. The QCSRP focused on the summer season in southeast Queensland with two field campaigns: December 2007–March 2008 and November 2008–February 2009.

To characterize the environment in which clouds were forming, regular flights were conducted to obtain measurements under the bases of clouds in the region. These measurements were collected with the instruments listed in Table 1 and have been used to document the concentration, size, and composition of aerosol particles entering the clouds, in particular those that serve as cloud condensation nuclei (CCN), which affect microphysical processes. Determining the aerosol properties in the region is the first step toward assessing the impacts of aerosol particles on rain formation.

To characterize the various aerosol conditions observed in the region, back trajectories[6] were calculated from each of the cloud-base aerosol measurements (see Fig. 4). A variety of influences were recognized, including maritime versus continental flow, and that some aerosol measurements may have been influenced by the city of Brisbane itself (e.g., 13 and 22 January; see inset map in Fig. 4). The aerosol and CCN concentrations support the back-trajectory variations from continental to maritime flow, with higher aerosol concentrations observed on days with more continental flow and cleaner (less aerosol) conditions on days with maritime flow.

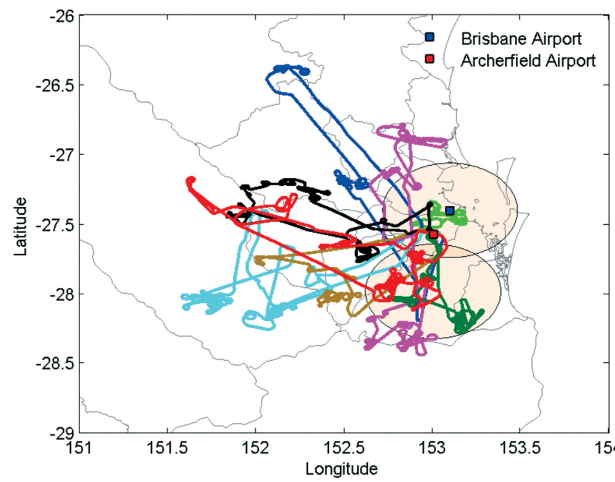

FIG. 3. Map of various flight tracks (each indicated by a different color) around the Brisbane region. The dual-Doppler lobes (from Fig. 1) are overlaid, and the Archerfield and Brisbane airports are highlighted for reference. Faint gray lines indicate the watershed boundaries in the region.

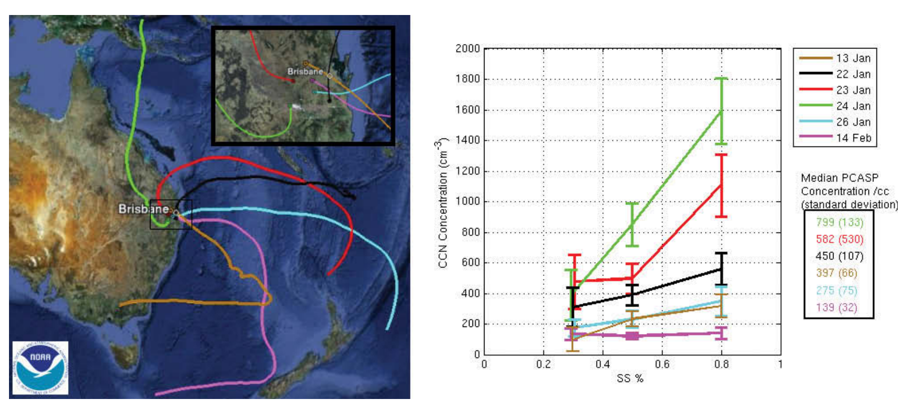

FIG. 4. (left) Map of 120-h HYSPLIT back trajectories for six sampling days in 2009 (13, 22–24, and 26 Jan, and 14 Feb) and (right) associated color-coded CCN concentration measurements at three supersaturations (0.3%, 0.5%, 0.8%) with whiskers indicating plus/minus one standard deviation for each filter sampling measurement (see legend). The median (and standard deviation in parentheses) PCASP aerosol concentration for each measurement is also noted by color for each day in the legend. An inset map is included to provide a zoomed-in view of the trajectory paths relative to the city of Brisbane.

6 Back trajectories were calculated with the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 1997)

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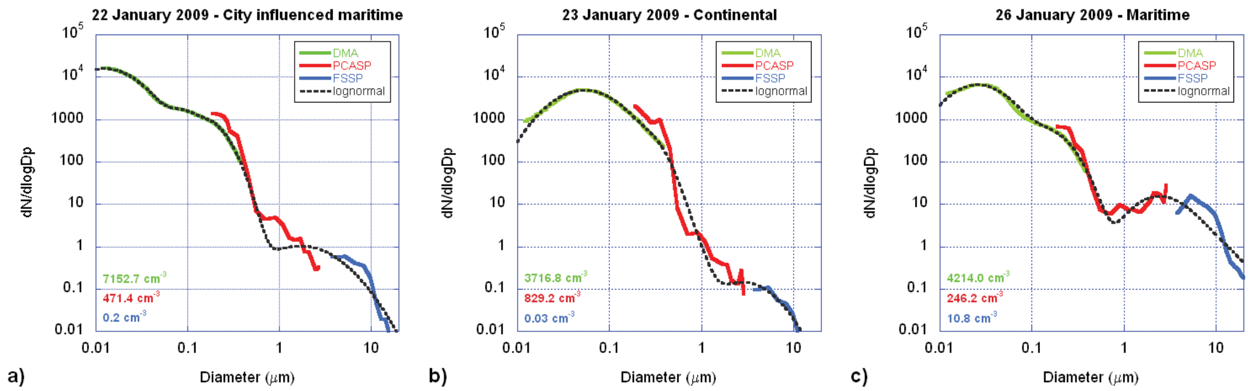

Fig. 5. Aerosol size distributions created from the DMA (green), PCASP (red), and FSSP (blue) measurements for (a) 22 Jan 2009, (b) 23 Jan 2009, and (c) 26 Jan 2009. A lognormal fit has been applied to the combined dataset based on methods in Hussein et al. (2005) and is overlaid as a black dashed line. The mean total concentration per probe (same color as distribution line) is indicated in the lower left corner.

In addition to the concentration of aerosol and CCN, the size distributions of the aerosol are also important for cloud microphysical processes. Larger (coarse mode) aerosol preferentially serve as CCN than smaller (fine mode) particles, and broader size distributions of aerosol can also lead to broader size distributions of cloud droplets as they nucleate on the aerosol particles, which can lead to more efficient collision and coalescence processes. The DMA, Passive Cavity Aerosol Spectrometer Probe (PCASP), and FSSP are probes that count and size the aerosol particles that when combined, cover a broad range of sizes (see Table 1). Examples of the aerosol size distributions measured by these three instruments on three different days are shown in Fig. 5—one with a maritime influence, one with a continental influence, and one with a maritime history that has been influenced by city of Brisbane (see Fig. 4).

To assess the composition of the aerosol, a three-stage particle impact sampler (MPS-3, California Measurements, Inc.) was used to collect aerosol particles during the QCSRP and then a transmission electron microscope (TEM) was used to determine the properties of the individual aerosol particles (Abel et al. 2003; Niemi et al. 2006; Adachi and Buseck 2008; Freney et al. 2009; Pósfai and Buseck 2010). Approximately 700 particles were studied from six sampling days in 2009 using a CM200 TEM, and of these approximately 70 particles were further examined using environmental transmission electron microscopy (ETEM) to study their response to humidification. Mineral dust, ammonium sulfate, sodium chloride, and magnesium-bearing organic particles were the major particle types observed (Fig. 6). Furthermore, particle compositions were distinctly different in

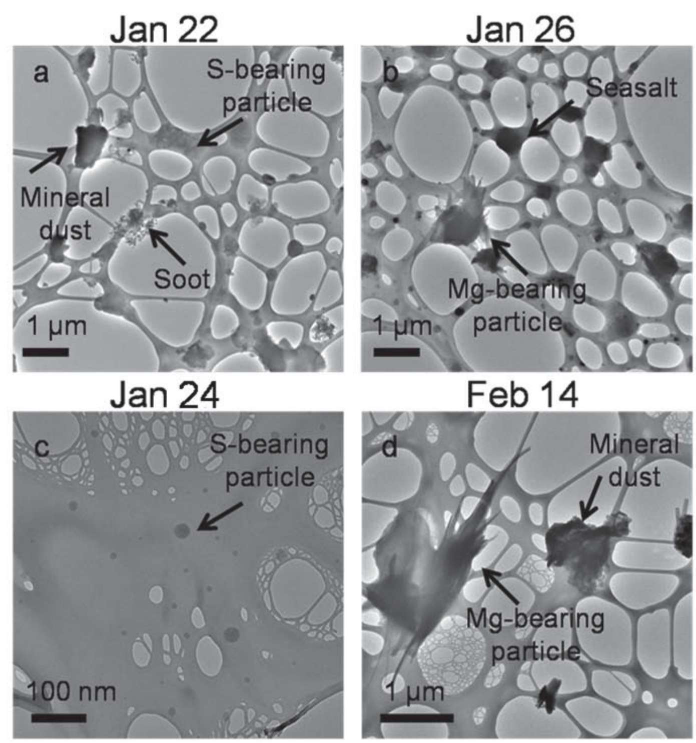

Fig. 6. Examples of particles collected during selected research flights. "S bearing" particles are sulfur bearing, and "Mg bearing" are magnesium-bearing particles. The fibrous, spider web-like material is the lacy-carbon substrate on which the particles were collected. The date on which particles were sampled is shown above each image, all of which occurred in 2009. Note the different scale for the 24 Jan image.

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the coarse and fine fractions of all samples studied with the TEM. Particles in the coarse fraction were almost exclusively mineral dust, whereas the fine-mode particle compositions were more variable in composition.

Days containing the highest number of sulfur-bearing particles in the fine fraction also had the highest CCN concentrations and had back trajectories indicative of continental or urban-influenced air masses (22, 23, and 24 January in Fig. 4). The more maritime-influenced cases, such as 26 January and 14 February, had the highest number of salt-bearing fine-mode particles while having the lowest aerosol and CCN concentrations overall (Fig. 4). These measurements help to quantify properties of the aerosol that impact cloud microphysical processes that our sizing and counting aerosol probes cannot provide, and they can help us validate our microphysical observations and models. Moreover, by linking the properties of the in situ aerosol measurements with properties of their back trajectories, we are working to develop a predictive tool for estimating the aerosol conditions at any given location in the region, which will be useful in future analyses for which we may not have direct in situ aerosol measurements.

Table 2. Examples from the literature of cloud drop measurements near cloud base in cumuliform clouds from various regions. ACE1 = the first Aerosol Characterization Experiment; ASTEX = Atlantic Stratocumulus Transition Experiment; PASE = Pacific Atmospheric Sulfur Experiment; SCMS = Small Cumulus Microphysics Study; INDOEX = Indian Ocean Experiment. Statistics listed in this table depend upon what was presented in the cited study. Note that calculation methodologies varied and that direct comparisons should be avoided. Rather, these values provide an indication of the range of measured drop concentrations and how they vary by region. Drop concentration statistics include flight-averaged drop concentrations or mean cloud maximum concentrations (ranges of the observations from a given study or plus/minus the standard deviation were also included when available). The diameters included are means, ranges of means, or means plus/minus the standard deviation. Cloud types included are cumulus (Cu), stratocumulus (StrCu), shallow boundary layer cumulus or stratocumulus (BL Cu or BL StrCu, respectively), and cumulonimbus (Cb). All measurements made with a FSSP except as noted, where * indicates drop impactor and ** indicates continuous Formvar replicator.

Location (notes)	Concentration (cc^{-1})	Diameter (μm)	Cloud type	Reference
Southwest Pacific (ACE1)	58 ± 32		BL StrCu	Yum et al. (1998)
Azores (ASTEX)	~100		BL StrCu	Duynkerke et al. (1995)
Caribbean (RICO)	111 ± 46	17.1 ± 2.1	Cu	Hudson and Mishra (2007)
Pacific Ocean (PASE)	139 ± 39		BL Cu	Hudson and Noble (2009)
Hawaii	148–170		Cu	Twohy and Hudson (1995)
Florida (SCMS maritime)	150 ± 49	15 ± 3.7	Cu	Hudson and Yum (2001)
Indian Ocean (INDOEX clean)	189 ± 64	13.7 ± 5.7	BL Cu	Hudson and Yum (2002)
Queensland (off coast)	300–450		Cu	Warner and Twomey (1967)*
Florida (SCMS continental)	312 ± 68	10.9 ± 0.9	Cu	Hudson and Yum (2001)
Queensland (QCSRP maritime)	332 ± 211	10.1 ± 2.3	Cu, Cb	Present study
Queensland (QCSRP continental)	425 ± 149	10.0 ± 2.1	Cu, Cb	Present study
Indian Ocean (INDOEX polluted)	478 ± 114	8.9 ± 1.1	BL Cu	Hudson and Yum (2002)
Florida (near-adiabatic SCMS)	487		Cu	Laird et al. (2000)
Queensland (near cane fires)	710–920		Cu	Warner and Twomey (1967)*
St. Louis (upwind)	689–927	8.1–8.9	Cu, StrCu	Fitzgerald and Spyers-Duran (1973)**
Montana	800–900	8–10	Cb	Dye et al. (1986)
St. Louis (downwind)	1,157–1,427	5.9–6.8	Cu, StrCu	Fitzgerald and Spyers-Duran (1973)**

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PRECIPITATION FORMATION STUDIES. In situ measurements of cloud droplet properties (Table 2), at altitudes just above cloud base up through the –12°C level, constituted the second step in assessing the impacts of the aerosol on rain formation. There has been a long observational history demonstrating that increasing continentality is normally associated with increasing CCN concentrations in the subcloud layer (Rosenfeld et al. 2008). As the CCN concentrations increase, so typically does the cloud droplet number concentrations near cloud base, which may also be accompanied by narrower cloud droplet spectra, thereby enhancing the colloidal stability of the clouds (Squires 1958). Thus, in theory, aerosol and CCN measurements beneath clouds should be highly correlated with the cloud droplet concentrations just above cloud base; however, making such comparisons is challenging, given the effects of varying supersaturation, entrainment of cloud-free air, and drizzle formation on in situ droplet measurements.

Despite these challenges and variable measurement methods utilized in the literature,[7] droplet concentrations have typically been observed to be much lower over the oceans than in continental or more polluted regions (Table 2), which is often related to regional aerosol content. The droplet concentrations measured just above cloud base in the QCSRP clouds[8] were most similar to those observed in other coastal locations, such as Florida, or in the polluted portions of the Indian Ocean, even when split by continental or maritime influence (see Table 2), indicating that the QCSRP region's range of drop measurements fall within an intermediate category on a global spectrum from clean to polluted conditions. The QCSRP measurements are in general agreement with the previous droplet measurements documented by Warner and Twomey (1967) that were collected in clouds off the coast of Queensland (and upwind of seasonal cane fires) north of the QCSRP domain 40 years ago.

Even though the effects of aerosol content and *cloud* droplet concentrations have been linked, the impact of varying CCN on precipitation efficiency and the resulting *raindrop* size distribution (DSD) is less established. Since the QCSRP observational domain was near the coast and varied synoptic conditions provided both continental and maritime surface flow, we expect clouds to exhibit some amount of variability in their raindrop characteristics, particularly in their early formation. The QCSRP provided a unique opportunity to investigate the use of polarimetric radar to observe such changes in the DSD that might be the result of aerosol or cloud seeding.

A polarimetric radar can estimate aspects of the DSD during the evolution of a storm by utilizing the differential reflectivity (Z_{dr}), which is the ratio between horizontal and vertical radar reflectivity factors[9] (Z_h and Z_v, respectively); Z_{dr} provides a measure of the oblateness of the raindrops, which increases with the size of the raindrops. Thus, Z_{dr} is related to raindrop size.[10] For reference, a monodisperse size distribution of raindrops 3.6 mm (5.8 mm) in diameter has a Z_{dr} of 2 dB (4 dB; Knight et al. 2002).

A number of studies have examined the use of Z_{dr} to estimate DSDs (e.g., Bringi et al. 1986; Wakimoto and Bringi 1988; Brandes et al. 2004). A Z_{dr}-based technique was used by Knight et al. (2008) to study the evolution of DSDs in trade wind cumulus in the northeastern Caribbean Sea during the Rain in Cumulus over the Ocean (RICO) experiment (Rauber et al. 2007). Here we compare the evolution of Z_h and Z_{dr} from the small, maritime clouds in RICO with those from the QCSRP to obtain a measure of the naturally occurring variability of the DSDs (Fig. 7). Knowledge of the natural variability of Z_h versus Z_{dr} is important when assessing any possible effects cloud seeding may have on the raindrop size distribution (Wilson et al. 2011).

The convective clouds studied (Fig. 7) were primarily individual single-cell storms that were not part of an existing cluster of precipitating clouds. There is a considerable difference between Figs. 7a and 7b, in that the maritime data from RICO are confined mostly between the two reference curves and that the QCSRP data have much greater scatter, particularly toward larger AZ_{dr} values. The fact that these larger values of AZ_{dr} at low values of AZ_h

[7] Several methods for calculating droplet concentrations from aircraft measurements have been explored in the literature and vary from flight-averaged concentrations to methods that attempt to identify concentrations in the near-adiabatic core of the clouds (Yum et al. 1998; Hudson and Yum 2001).

[8] The "binmax" method (from Yum et al. 1998) has been used for the QCSRP droplet measurement statistics presented in Table 2.

[9] In this paper, all radar reflectivities are equivalent to radar reflectivity; however, for simplicity, the subscript *e* is not used.

[10] For more information on polarimetric radar variables, see Doviak and Zrnić (1993) or Bringi and Chandrasekar (2001).

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are mostly during the growing phase of the clouds shows that in Queensland, the initial precipitation formation can have a very bimodal DSD, with Z_h dominated almost completely by very sparse raindrops in some clouds. It is worth noting that the RICO data represented warm clouds (tops warmer than freezing) almost exclusively, and that the QCSRP clouds were a mixture of warm and cold clouds from both maritime- and continentally influenced environments. Wilson et al. (2011) studied these trends in more detail on a case-by-case basis for 45 cells in Queensland and found two general types of raindrop size evolution patterns. From their analysis, Wilson et al. concluded that the ice phase does not likely influence the differences observed. Rather, they found that the two general raindrop size evolution types were most likely related to the continentality of the air mass, based on its back trajectory: one associated with air masses that were maritime in nature and the other with more continental air masses.[11] Moreover, their analysis documents the variability of the DSD even over the lifetime of a single cloud, and thus it highlights the need to analyze such effects at a similar stage of cloud growth (i.e., the early growth stage) to prevent any possible microphysical signals from being masked by the noise of natural variability (see sidebar for information about direct measurements of raindrop size).

Bringi et al. (2002, 2003, 2009) developed a methodology for retrieving parameters of the DSD with polarimetric radar variables. They showed that when the DSD is described by a gamma distribution, it can be succinctly described by size and concentration parameters: D_0, the mass-weighted mean diameter, and N_w, the drop number concentration. Using climatological

[11] The continentality of an air mass may be defined by variable aerosol properties (recall Fig. 4) but also by variable cloud-base heights and subcloud moisture, which affect a cloud's liquid water path. Several recent studies have cited the importance of liquid water path on precipitation formation (e.g., Stevens and Feingold 2009; Sorooshian et al. 2009), and thus this effect needs to be considered in addition to potential aerosol effects as the cause for observed microphysical differences.

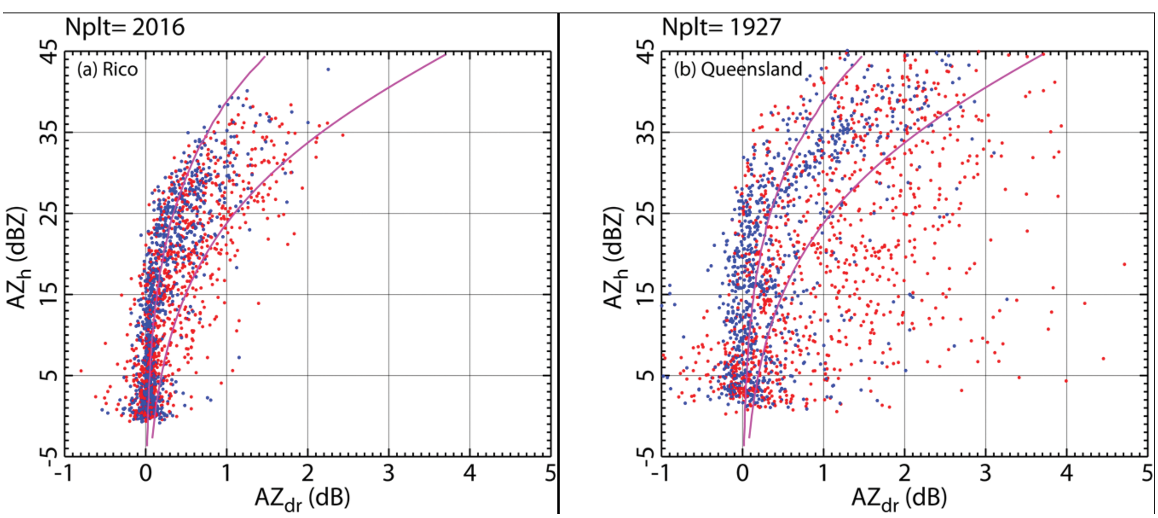

Fig. 7. Scatter plots of AZ_h versus AZ_{dr} for (a) the maritime Caribbean environment from RICO (190 clouds) and (b) Queensland from the QCSRP (30 clouds). The letter A is used to signify that the individual points represent area Z_h and Z_{dr} values that are calculated for the whole sweep (single elevation angle) through the cell, which is *not* equal to averaging over all of the individual pulse-volume values but by calculating the values the sweep would have as a single pulse volume (as was done in Knight et al. 2008). The data points represent multiple heights and multiple times through the life of the convective cells. For ease of viewing and comparison with Queensland, only every sixth point has been plotted for the RICO data. The number of points in each plot is denoted by "Nplt" at the top of each panel. Red points represent scans during the growing phase of a cloud, defined as increasing total-volume values of Z_h. Blue points represent decreasing Z_h. Following the procedure in Knight et al. (2008), two reference curves are included: the curve to the left is expected from a Marshall–Palmer distribution, while that to the right is from single-sized water drops at a 1 m^{-3} concentration. This is meant to approximate an extremely bimodal distribution for which the smaller mode contributes negligibly to Z_h and the larger mode is sparse raindrops. [From Wilson et al. 2011.]

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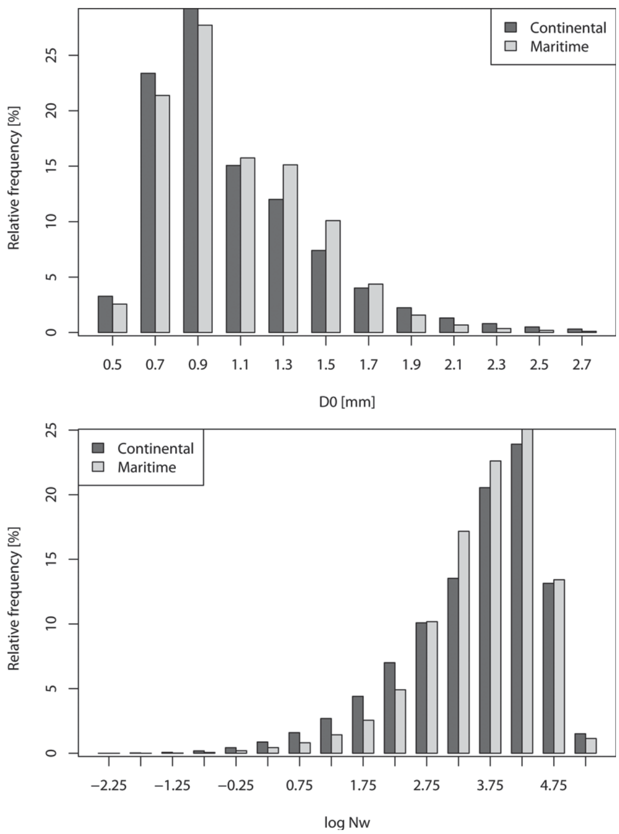

disdrometer data, D_0 and N_w can also be used to derive rain rates (Bringi et al. 2009). The methodology has recently been employed to examine differences in rain rates and DSDs in different climatic regimes (Bringi et al. 2003; Thurai et al. 2010). Furthermore, May et al. (2011) applied the technique to storms with similar dynamic and thermodynamic characteristics, thereby isolating the effects of aerosol on a deep convective storm. This type of analysis has also been proposed for the QCSRP to investigate whether aerosol effects are observable in radar-retrieved DSDs. As a demonstration of this technique, four days were chosen to illustrate DSD characteristics of Queensland clouds: two days with maritime flow and two days that were continentally influenced (Fig. 8). These initial results show that differences between D_0 and N_w for all clouds occurring over entire days with maritime and continental influences are subtle, and that future

Fig. 8. Histogram comparisons of probability distributions for radar-retrieved DSD parameters (top) D_0 and (bottom) log(N_w) from CP2 radar data for continental- and maritime-influenced flow conditions; D_0 is the median volume diameter, and N_w is the "generalized" intercept parameter, which is related to the concentration. The continental flow conditions were obtained from all quality-controlled CP2 data sweeps on 23 and 24 Jan 2009, while the maritime cases were obtained in the same manner on 13 and 26 Jan 2009. The airmass trajectories and subcloud aerosol characteristics for these days are presented in Fig. 4.

DIRECT MEASUREMENTS OF RAINDROP SIZE

Direct measurements of the DSD in rain can be measured by raindrop disdrometers; however, such measurements are taken at the surface and may not reflect the DSD in the cloud, which is what is measured by radar. Nonetheless, raindrop disdrometers offer guidance on the relationship between reflectivity and differential reflectivity in convective rainfall (Fig. SB1). Intense rainfalls typically are associated with larger drops (high reflectivity) that are more oblate (large differential reflectivity). Light rainfall rates are usually characterized by small, near-spherical drops (low reflectivity and differential reflectivity). The correlation between variables is generally reduced (noisier) for radar-based measurements, however. As a difference quantity, the differential reflectivity is sensitive to issues regarding precipitation gradients, statistical error in the measurements, radar sidelobes, ground clutter contamination, and the presence of hail and insects. Hence, radar-derived distributions of reflectivity and differential reflectivity may often show more scatter, as is the case in Fig. 7. A potential issue with disdrometer observations, nonetheless, is the limited sampling of large drop concentrations.

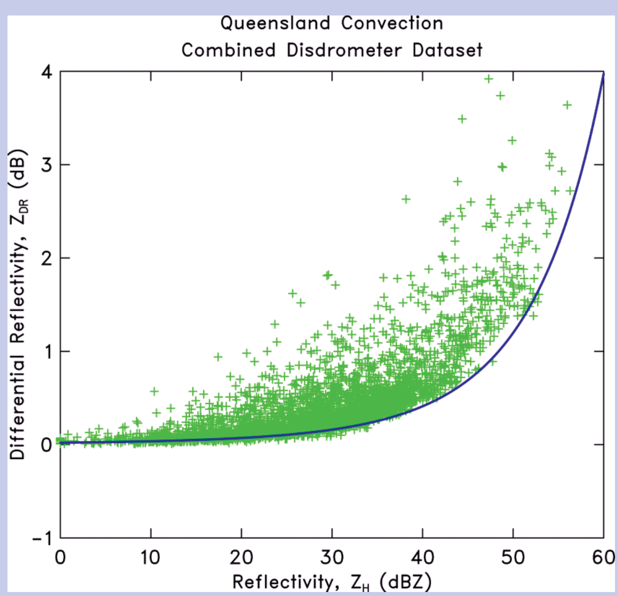

Fig. SB1. Radar reflectivity plotted vs differential reflectivity, as calculated from disdrometer observations for convective rainfall in Queensland (3,396 1-min samples).

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focus should be on comparing observations at similar stages of the microphysical evolution of clouds[12] and for clouds with similar dynamic and thermodynamic characteristics to isolate potential aerosol effects on raindrop size and concentration.

Thermodynamic and dynamic considerations. The thermodynamic profile of the storm environment influences the height and temperature of the cloud base and the portion of the cloud that is warmer or cooler than freezing, and thus whether warm or cold cloud microphysical processes will be affecting precipitation formation. The vertical velocity of a cloud is indicative of the dynamic intensity of the system and is dependent on the buoyancy of the rising air parcel that is creating the cloud, which is also determined by the environmental thermodynamic profile. The buoyancy of a rising air parcel may also be influenced by aerosol microphysical effects through the release of latent heat of condensation and, in mixed-phase scenarios, fusion. In the QCSRP, dual-Doppler measurements with the CP2 and Mt Stapylton radars were available and thus the three-dimensional wind field, including the vertical velocity, can be retrieved to directly estimate the dynamics of the observed storms. Figures 9 and 10 present examples of the dual-Doppler wind retrieval[13] for two very different storm cells that initiated in the same location five hours apart. Subcloud aerosol conditions between the two were similar with PCASP concentrations between 500 and 550 cm^{-3}. Figure 9 highlights the difference in vertical extent and intensities of reflectivity and updrafts between

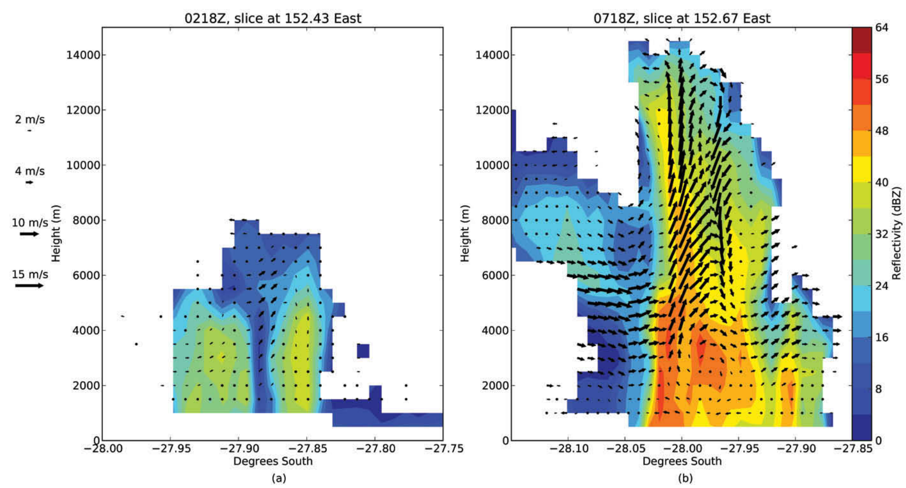

Fig. 9. Vertical cross sections of CP2 radar reflectivity (color contours; scale on right) and dual-Doppler-derived storm vertical motion vectors at constant longitude (152.43°E) for (a) shallow (0218 UTC) and (b) deep (0718 UTC) precipitating systems on 23 Jan 2009.

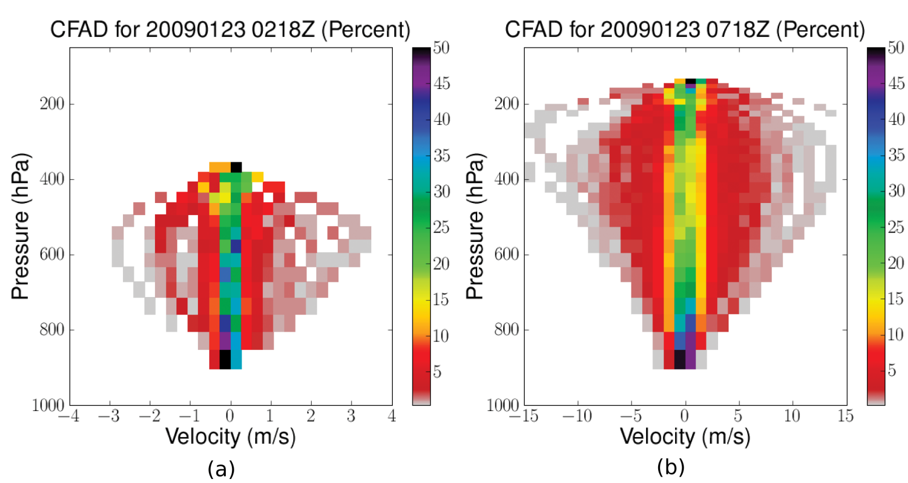

Fig. 10. CFADs (Yuter and Houze 1995) of vertical motion for the two storms depicted in Fig. 9 from 23 Jan 2009 at (a) 0218 and (b) 0718 UTC. Note difference in the velocity scale between the two panels. Each color represents the frequency (as a percentage of the total storm volume) that a given vertical velocity occurred at a given height.

[12]Recall that the results from Wilson et al. (2011), which were focused on individual clouds not entire days, highlighted that microphysical differences between clouds within the maritime and continental regimes were most evident only in the growth phase of a cloud.

[13]The retrieval of the velocity structure presented herein is from gridded radar moments using gridding methods from Mohr and Vaughan (1979) and Collis et al. (2010) and a variational algorithm that is an adaptation of the technique first reported in Ray et al. (1980) and further refined by Scialom and Lemaître (1990) and Protat and Zawadzki (2000).

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the two storm cells. Contoured frequency by altitude diagrams (CFADs; Yuter and Houze 1995) contrast the structure of vertical velocity for these two storms (Fig. 10). CFADs are a commonly used technique for quantifying characteristics of storm vertical structure over large volumes of radar data (see Cifelli et al. 2007; Stephens and Wood 2007). The CFADs show the difference in maximum updraft and downdraft magnitudes between the two storms as well as heights and frequencies of these maxima (Fig. 10).

Thermodynamic considerations add a substantial challenge to investigating the impact of cloud–aerosol and/or cloud seeding interactions on the microphysics and the dynamics of precipitating systems. The analysis highlights presented in Figs. 7 and 8 were composed of clouds that formed under different thermodynamic/dynamic conditions; therefore, the observed differences in the DSD characteristics could be due to these factors rather than variations in the subcloud aerosol. Nonetheless, we aim to utilize the techniques presented herein for assessing microphysical differences that could be due to aerosol and cloud seeding, especially the effect of cloud seeding on the DSD, by normalizing by cases with similar stability and airmass histories. Dual-Doppler air motion retrievals could be used to isolate cases of similar intensity by being able to stratify by updraft velocity, for example (or use CFADs to stratify by cases with similar vertical structure of the updraft velocity), and then look for microphysical effects under similar thermodynamic and dynamic conditions.

CHALLENGES. The observational infrastructure in the QCSRP provided an opportunity to validate the physical chain of events of the hygroscopic seeding conceptual model through the ability to seed and measure storms at the same time (using both aircraft), to document microphysical characteristics and development both in situ (aircraft) and remotely (polarimetric radar), and to assess dynamic responses through dual-Doppler radar analysis. However, a number of physical and logistical constraints prevented us from being able to take regular in situ measurements at key heights (within 1,000 ft of cloud base[14]) and times for cloud droplet nucleation in seeded clouds.

The first constraint was due to air safety regulations in Australia that prevented us from flying both aircraft simultaneously with less than 2,000 ft of vertical separation; so, if the seeding aircraft was at cloud base, the research aircraft had to be at least 2,000 ft above cloud base. Furthermore, the air traffic control (ATC) system was quite busy with its normal load of air traffic in the controlled air space around Brisbane, which made it difficult to get clearances to fly the two aircraft in coordinated flight patterns as well as to be able to target specific clouds at the right times. Nonetheless, we were able to simultaneously measure nearly one-half of the randomized cases targeted by the seeding aircraft in the first season with the research aircraft. Furthermore, this issue was somewhat alleviated in the second field season, having just one aircraft and because we held regular briefings with ATC to inform them of our intended flight plans. In doing the latter, ATC was better prepared to handle our unique requests, and we gained a better appreciation of what requests were likely to not be granted because of their operational constraints.

The physical terrain in the region also served as a constraint on our flight capabilities that unfortunately cannot be avoided with current aviation navigation technology. The minimum safe flight altitudes for flying in clouds (no visibility) over areas with higher terrain were often several thousand feet above cloud base. Moreover, certain clouds were unable to be targeted for hygroscopic cloud seeding at cloud base if they were initiated over the higher terrain areas and the cloud base was lower than the terrain height. These terrain issues (especially the minimum safe altitude rule that prevented measurements at 1,000 ft above cloud base) impacted roughly one-quarter of the flights. These conditions made it unsafe and logistically impossible to fly an aircraft in those target areas. Therefore, other in situ measurement and seeding techniques would need to be developed for such conditions.

Besides these physical and logistical constraints, another challenging issue for cloud seeding research experiments is to seed at the appropriate time (Tzivion et al. 1994; Reisin et al. 1996). By the time a radar echo appears on precipitation radar for a typical airmass storm, it already has precipitation that has formed and may often already be dissipating. Thus,

[14]Droplet spectra should be established by this height, and natural droplet spectral broadening processes start to occur above this height. Inconsistent measurement heights make it difficult to then identify if a measured droplet spectra was broader (or narrower) because of nucleation on ambient CCN spectra or cloud seeding particles versus natural broadening processes. There is unfortunately no way to correct this discrepancy, as the rate of droplet growth and spectral broadening depends on many variables, including supersaturation (i.e., updraft speed and the initial CCN spectra).

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using precipitation radar to guide the aircraft often results in seeding after the peak updraft has occurred. Furthermore, without having a tracer released concurrent with the seeding material (and an appropriate instrument on the research aircraft to measure said tracer), it is not trivial to determine whether the research aircraft flew through a portion of the cloud affected by the seeding material or not. In Queensland, we did not employ a tracing capability because of the limitations of current tracing technologies (e.g., chaff or sulfur hexafluoride gas); however, this severely limited our dual-aircraft cloud seeding detection capabilities. Thus, we would highly recommend the development and use of effective tracers for future experiments.

FUTURE EFFORTS. Despite the challenges, this kind of analysis of combining state-of-the-art instrumentation and observations to improve our physical understanding of microphysical processes is relevant and necessary for any observational studies investigating aerosol or cloud seeding microphysical effects. We learned that having a better understanding of the natural variability would be a helpful precursor to conducting a randomized seeding experiment, and we recommend utilizing that knowledge by perhaps only targeting clouds that fit a certain thermodynamic and aerosol profile to reduce some of the variability among the randomized population that will be used for statistical analysis.

There is a great opportunity for a lot of research combining all of the data that were collected in the QCSRP to study aerosol and cloud seeding effects on microphysical processes. The unique dataset collected during the extensive time in the field [typical field campaigns have intensive observing periods (IOPs) on the order of 1–2 months, whereas this experiment ran for 4 months] is available for such studies, and we encourage collaboration within the community to address the issues related to understanding aerosol microphysical interactions from both observational and numerical modeling approaches. For example, the knowledge we have gained about the natural variability in the region now needs to be utilized to help constrain detailed case studies of the microphysics (using the multiparameter radar data and in situ measurements) to study impacts on precipitation processes, such as secondary ice production and precipitation efficiency. Future studies could also address how changes in cloud microphysical processes may alter the updraft/downdraft structure and subsequent dynamics of cloud systems by utilizing the polarimetric and dual-Doppler radar data from the project. In particular, modeling studies are also needed to help fill some of the gaps that the observational constraints have left open. A parcel or bin microphysics modeling approach could address questions regarding the timing from cloud to rain formation under various aerosol conditions (including those perturbed by hygroscopic seeding). These models can hold thermodynamic parameters constant and use the observations to help constrain the results to assess the impacts of aerosol on rain formation.

As more stress is placed on water resources in our changing climate, especially in already arid regions and those with rapidly growing populations, this area of research is of vital importance for communities to develop successful water management strategies. Nonetheless, the large-scale drivers of climate [especially the El Niño–Southern Oscillation (ENSO) phenomenon, low-frequency systems related to decadal and interdecadal Pacific Ocean sea surface temperatures, as well as aspects related to climate change] are still clearly dominant factors when it comes to long-term precipitation patterns, as is evidenced by the reversal of southeast Queensland's drought from a few years ago to the recent devastating floods the region has experienced. This in itself introduces another set of challenges associated with the effects of such extreme climate shifts on society, and how the public will perceive and adapt to each extreme. Cloud seeding is one possible avenue that some communities have pursued (and welcomed) to mitigate water shortages, but it could easily be blamed for disastrous flooding when the opposite situation arises. Thus, scientists conducting cloud seeding research efforts need to be cautious in their approach, and they should include interdisciplinary teams that integrate input from many scales of decision making, scientific knowledge, and public opinion.

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Faculty Position Opening in Meteorology
Florida Institute of Technology • College of Engineering
Department of Marine and Environmental Systems

The Florida Institute of Technology seeks to fill a full-time faculty position in meteorology. Candidates are welcome from all atmospheric science disciplines, but the successful applicant will be expected to teach both graduate and undergraduate courses including synoptic meteorology, atmospheric remote sensing, and dynamical meteorology, and to conduct externally-funded research on vital contemporary issues. The applicant must have an earned doctorate in meteorology or atmospheric science, and a strong commitment and potential for teaching, research, and service. Salary and academic rank are commensurate with experience; however we expect to fill the position at the assistant or associate professor level. The position is available August 2012, but will remain open until filled.

To apply, please send copies of an application letter, curriculum vitae, and the name, postal, and email address of three references to:

Professor George A. Maul, Head
Department of Marine & Environmental Systems
Florida Institute of Technology
150 West University Boulevard
Melbourne FL 32901

For further information see http://coe.fit.edu/dmes; or call 321-674-8096; or email gmaul@fit.edu.

Florida Tech is an equal opportunity employer committed to excellence through diversity.

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