Atmospheric Research 193 (2017) 173–183

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Invited review article

Modern and prospective technologies for weather modification activities: Developing a framework for integrating autonomous unmanned aircraft systems

T.P. DeFelice[a,*], Duncan Axisa[b]

[a] Sykesville, MD, USA
[b] Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO, USA

ABSTRACT

This paper builds upon the processes and framework already established for identifying, integrating and testing an unmanned aircraft system (UAS) with sensing technology for use in rainfall enhancement cloud seeding programs to carry out operational activities or to monitor and evaluate seeding operations. We describe the development and assessment methodologies of an autonomous and adaptive UAS platform that utilizes in-situ real time data to sense, target and implement seeding. The development of a UAS platform that utilizes remote and in-situ real-time data to sense, target and implement seeding deployed with a companion UAS ensures optimal, safe, secure, cost-effective seeding operations, and the dataset to quantify the results of seeding. It also sets the path for an innovative, paradigm shifting approach for enhancing precipitation independent of seeding mode. UAS technology is improving and their application in weather modification must be explored to lay the foundation for future implementation. The broader significance lies in evolving improved technology and automating cloud seeding operations that lowers the cloud seeding operational footprint and optimizes their effectiveness and efficiency, while providing the temporal and spatial sensitivities to overcome the predictability or sparseness of environmental parameters needed to identify conditions suitable for seeding, and how such might be implemented. The dataset from the featured approach will contain data from concurrent Eulerian and Lagrangian perspectives over sub-cloud scales that will facilitate the development of cloud seeding decision support tools.

1. Introduction

Present-day weather modification technologies are scientifically based and have made controlled technological advances since the late 1990′s, early 2000′s. The technological advances directly related to weather modification have primarily been in the decision support and evaluation based software and modeling areas (Axisa and DeFelice, 2016). There have been some technological advances in other fields that might now be almost ready for successfully optimizing weather modification science and seeding methodology. Weather modification technologies may be effectively applied to facilitate the water cycle efficiencies. Hence a need to develop the science and integrate newer operationally viable technology that will improve the appropriate systems used to identify and monitor seeding conditions within suitable clouds should remain at the forefront of current research.

In both glaciogenic and hygroscopic seeding, seeding material must be properly applied to be effective. This is often referred to as 'targeting' (e.g., Keyes et al., 2016; ANSI/ASCE/EWRI, 2017). Models that provide decision support relative to targeting, for example, have come a long way over the years, but in most cases model performance is not evaluated adequately due to lack of suitable observations in space and time. Model errors are uncharacterized which may lead to incorrect model guidance and seeding actions. In parallel, the innovation in real time sensor based seeding guidance in rainfall enhancement programs has been slow and little progress has been made in precise targeting of suitable clouds.

Unmanned aircraft systems (UAS) with simple payloads can measure meteorological state parameters, wind and turbulence, aerosol and cloud microphysical properties and other variables in conditions that are conducive to cloud seeding to improve, validate and monitor operational weather modification activities. The capabilities of UAS have increased dramatically over the past decade, especially with improvements in autonomous flight performance. Axisa and DeFelice (2016) make a case for their potential usefulness in cloud seeding

---

[*] Corresponding author.
E-mail address: clddoc1@gmail.com (T.P. DeFelice).

http://dx.doi.org/10.1016/j.atmosres.2017.04.024
Received 14 December 2016; Received in revised form 5 April 2017; Accepted 11 April 2017

Table 1
Functional definition of a UAS to identify and monitor cloud seeding opportunities.
(Adapted from Axisa and DeFelice (2016)).

Function	Capability ([b])
Sensing	Atmospheric profiles surface to flight-level: air temperature, dewpoint temperature, wind field, turbulence, static pressure, spectral irradiance, supercooled liquid water content (SLW) Atmospheric constituents (aerosols, cloud, precipitation, trace gases, total water content) Surface characteristics (temperature, moisture content, spectral reflectance, soil moisture, soil temperature profiles) Ancillary, auxiliary (e.g. GPS, platform velocity, acceleration, attitude, pitch, roll, video) [e.g. AgI, dry ice (DI), hygroscopic agent dispenser]
Sensor coverage	Omni-slight skew toward forward hemisphere; [Sub-UAS point[a] (AgI; DI)]
Data processing	Able to process hundreds of Terabytes of data per second; functional tools, decision support; calibration/validation; archive; [Seed start and stop, GPS locations, amount AgI/DI dispensed]
Software	Algorithms to yield required information: Capability Maturity Model Integration, level III (CMMI III). Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR)[c]; data logging; data processing; [Algorithms to yield required information (e.g. seeding decision), control operations (e.g. ignite squib-burn AgI solution/flare or other, flight path,); data logging; data processing]

[a] Sub-UAS Point is defined as the "point of intersection with the earth's surface-geoid of a plumb line from the UAS to the center of the Earth" (i.e., intersects surface at a 90 degree angle).

[b] Additional configuration included to conduct cloud seeding operations is enclosed in square brackets.

[c] A C4ISR component not only acts as the "brains" of the payload, it is also used to support targeting of the seeding agent to ensure the material reaches the right place, at the right time.

operations and their evaluation, and provide a high-level programmatic foundation underlying the development of new sensing technologies and their integration with UAS for use in weather modification activities. DeFelice and Axisa (2016) continued to develop the framework for integrating autonomous unmanned aircraft systems into cloud seeding activities. The ability to send a UAS on a mission without the need for a pilot greatly expands the potential for extended cloud seeding operations while simultaneously lowering the operational footprint. Their application in mountainous terrain, as well as in arid and semi-arid regions of the world, and in water-stressed regions with limited infrastructure, presents new opportunities to expand rainfall enhancement programs in areas that have been previously overlooked.

Axisa and DeFelice (2016) defined two required basic functions of an unmanned system used for cloud seeding operations, namely to (a) identify atmospheric conditions conducive to seeding, and (b) implement the seeding. This paper describes development and assessment methodologies of an autonomous and adaptive UAS that utilizes in-situ and remote real time data to sense, target and implement guidance of rainfall enhancement operations based on an engineering and scientific process-based framework described in DeFelice and Axisa (2016). The UAS would be guided by remote sensors, typically ground radar systems, to provide target locations for the seeding and contain a sensor suite that provides 'in-situ' environmental parameters needed to identify conditions suitable for seeding. Trade studies designed to identify the most aerodynamic and balanced technical sensor solutions for this application would ensure the sensor operational readiness and would also test an improved weather radar algorithm that provides detection of early storm echoes for cloud targeting using the 'in situ' sensor data. The combination of 'in situ' sensor data and improved radar algorithms would enhance the ability to target optimal seeding conditions. The latter technique is referred to as adaptive control (Dydek et al., 2013), where UAS control systems offer improved performance and increased robustness by virtue of their ability to adjust their flight path as a function of measurements. In this paper we explore a framework to lay the foundation for future implementation of UAS in weather modification through adaptive autonomy, and in doing so we set a standard that is based on long-established engineering and scientific fundamental principles and industry best practices.

2. Background

The extent of drought and drought-like conditions trends toward record breaking coverage across much of the globe (e.g., McNutt, 2014; Cook et al., 2015; Ficklin et al., 2015; Zhao and Dai, 2015; Blunden and Arndt, 2016). Climate change is expected to increase drought severity in both moderate and high future emissions scenarios (Cook et al., 2015). Trends in drought are linked to changes in the hydroclimate cycle and can have a significant impact on human and natural systems (Ficklin et al., 2015). Globally, areas under severe drought greatly increased from 8% at the end of 2014 to 14% by the end of 2015 (Blunden and Arndt, 2016). McNutt (2014) links drought to a dwindling food supply as underground aquifers and water storage are extensively mined. The trends in drought are global as agricultural drought could increase relatively by 50%–100% by the 2090s (Zhao and Dai, 2015). Hence an urgent need exists to develop the science and technology for monitoring and managing atmospheric water. Better technology, appropriately designed and implemented to improve the efficiency of cloud seeding and independently verify such, will yield more water returned to the surface in the form of precipitation. More precipitation will help resolve the direct and indirect issues related to drought.

Cloud seeding technologies may be effectively applied (ANSI/ASCE/EWRI, 2013; ANSI/ASCE/EWRI, 2015; Keyes et al., 2016; ANSI/ASCE/EWRI, 2017) and thence facilitate the water and energy cycles (DeFelice et al., 2014), which are key to dealing with many present and potential future scientific, environmental, public concerns, and socio-economic issues. This concept paper builds upon the basic context and initial guidance for weather modification operators that might integrate UAS technology in future cloud seeding operations provided recently by Axisa and DeFelice (2016). Axisa and DeFelice (2016) defined cloud seeding operations and research with the greatest need for advanced technology and technique development into three functional components: (a) cloud seeding activity monitoring and simulation, (b) seeding agent delivery and dispersion, and (c) cloud seeding evaluation technology, techniques and protocols. Instrumented UAS technology was determined to be at the operational or near operational readiness level and therefore suitable for integration in cloud seeding operations. They identified the primary issues with UAS integration, noting such were most likely related to government policy, technology advancements, and operational considerations. They formulated a conceptual configuration for operations and for evaluation of the operational use of UAS for modern cloud seeding operations (Table 1). The authors anticipate that the challenges with UAS integration are likely to be overcome in the next decade. Airframes are becoming more reliable and economical to operate, the airspace system is opening up to UAS and recent developments have been made with microparticles/nanoparticles that could make them useful as seeding agents for weather modification activities (e.g. Luo et al., 2005; Carrasco et al., 2009; Zhang et al., 2009). The nanoparticle evolved from the material science work by Luo et al. (2005), while

Zhang et al. (2009) experimented with a hygroscopic nuclei coated with titanium dioxide. Laboratory experiments show the hydrophilic titanium dioxide coating improves the ability for the hygroscopic nuclei to adsorb and condense water vapor, compared to the uncoated hygroscopic nuclei.

The use of UAS in operational cloud seeding operations also has benefits that go beyond overcoming some of the operational safety concerns encountered by manned aircraft. They also provide:

– a cost effective means to evaluate cloud seeding using near real-time cloud system relevant measurements for evaluating the operations,

– a cost effective means to advance our understanding of the relevant science and engineering aspects, and

– a framework for application to other science and engineering areas.

For example, using UAS in tandem to gain the ability for cost effective, concurrent, real-time Eulerian and Lagrangian analyses of seeding processes throughout cloud life cycles on sub-cloud scales is unique to UAS applications. Flying manned aircraft in tandem is operationally challenging but often required for testing new seeding material, for example. The Eulerian and Lagrangian approach would benefit other disciplines including climate change, forecasting extreme and severe weather, flooding, drought and the impacts of such events on society, the economy and more. Axisa and DeFelice (2016) provide a more detailed list of benefits.

Unmanned aircraft systems (UAS) have been used in meteorological and other environmental applications since at least the 1990′s (e.g., Loegering, 2002; MacDonald, 2005; Fahey et al., 2006; Ramana et al., 2007; Scheve, 2008; NRC, 2009; Newman and Fahey, 2010; Frew et al., 2012; Hoff et al., 2012; Bates et al., 2013; Braun et al., 2013; Gupta et al., 2013; Hood, 2014; Sippel et al., 2014; Axisa and DeFelice, 2016; Jensen et al., 2017). Research has begun to use wind field and other environmental state parameters (e.g., air temperature, dewpoint temperature) to help prolong flight duration (e.g., Emmitt et al., 2014) and UAS technology has been shown capable of producing valid accurate data to model and simulate cloud processes (dynamics and microphysics) under a wide range of natural environments (e.g., Newman and Fahey, 2010; Frew et al., 2012). Hence we envision their usefulness as another tool to help improve seeding operations and quantify seeding efficiency (Axisa and DeFelice, 2016).

The configuration of a UAS for cloud seeding under either mode in Table 1 would be the ultimate goal. In practice, one would start with a much simpler version of the configuration in Table 1, guided by the modern-day cloud seeding operational capabilities (ANSI/ASCE/EWRI, 2013; ANSI/ASCE/EWRI, 2015; Keyes et al., 2016; ANSI/ASCE/EWRI, 2017).

Precipitation enhancement projects have been conducted primarily in regions where orographic clouds (those developed by the lifting of moist air as it flows over elevated topography) are common in the cold season, or where warmer-season cumuliform clouds are generated by vigorous convection, since the mid-1940s (Schaefer, 1946) based on the scientific principles of the precipitation process (e.g., Bergeron, 1935; Findeisen, 1938). Simply stated, cloud seeding is conducted on cloud systems or portions of clouds that are naturally inefficient at converting their moisture into precipitation, hence, cloud seeding makes clouds more efficient precipitators. Operational cloud seeding projects have been conducted since the first tests of both dry ice (Schaefer, 1946) and silver iodide, AgI (Vonnegut, 1947, 1981), as cloud seeding materials (e.g., Dennis, 1980; Marwitz, 1986; Keyes et al., 2016; ANSI/ASCE/EWRI, 2017). Cloud seeding to enhance winter snowpack in western mountainous areas has been considered highly successful since the mid-1980s (Elliott, 1986). The results of mixed phase convective cloud seeding have been mixed and often inconclusive. The seeding of isolated individual clouds has led to definite, mostly positive changes in the precipitation amounts (e.g., Dennis, 1980; Silverman et al., 1999; Woodley et al., 2003a, 2003b; Woodley and Rosenfeld, 2004; Rosenfeld et al., 2010; Keyes et al., 2016). Woodley and Rosenfeld (2004) developed and tested a computerized method for the objective evaluation of short-term, non-randomized operational convective cloud seeding projects on a floating-target-area basis. Their results indicated that rainfall was increased downwind of the seeding activity, primarily as the seeded clouds moved out of the target and into downwind areas. Downwind, or extra-area, effects are further discussed by DeFelice et al. (2014). Cloud seeding program evaluations have been used to gauge operational efficiency of the seeding operation, and when successful a benefit/cost ratio > 200/1 can be achieved (e.g., Axisa, 2004).

Airborne cloud seeding with glaciogenic materials (i.e., AgI, dry ice) is applied to clouds that contain high concentrations of supercooled liquid water. Glaciogenic seeding, whether seeding near cloud base or cloud top, requires updrafts strong enough to carry the seeding material to the optimal vertical cloud level where they will activate the precipitation process. Seeding with AgI material is conducted from near or at cloud base with strong updrafts or at cloud top depending on conditions, whereas dry ice is typically used via aircraft just inside or immediately above cloud top depending on conditions. There are rare cases where ground seeding of convective storms can be effective (Dessens et al., 2009, 2015; Berthet et al., 2013). Additional details of the seeding materials and their use in cloud seeding may be found in Keyes et al. (2016); ANSI/ASCE/EWRI (2017).

Cloud seeding may also be conducted in clouds too warm for AgI and dry ice, known as warm cloud seeding or hygroscopic seeding, for example:

– Mather et al. (1997) have carried out hygroscopic seeding experiments in South Africa and show convincing evidence of increases in the radar-measured rain mass from seeded storms;

– Silverman et al. (1999) report statistical significance and substantial increases in radar-estimated rainfall (ranging from 30% to 60%) from the seeded clouds using hygroscopic seeding techniques;

– Warburton et al. (1995) and Rosenfeld et al. (2010), for example, report a broadening of the drop size distribution following the seeding of continental convective clouds with hygroscopic salt powder, indicating that the salt material was acting to accelerate the warm rain process.

Hygroscopic seeding usually occurs just below cloud base, in clouds that are microphysically continental (i.e. contain high concentrations of small drops due to the absence of large hygroscopic aerosols), in the area of maximum updraft to ensure that the cloud ingested the seeding agent, and early in the convective cloud's lifetime. In this paper we focus on technology and techniques that target warm convective clouds for hygroscopic seeding.

3. Setting the boundary-conditions for our evolving framework

Our approach assumes two UAS flying in tandem in the vicinity of convective clouds. The UAS would have a similar payload and endurance. The two UAS, i.e., UAS1 (above cloud formation level/spotter) and UAS2 (near cloud formation level/seeder), equipped with video cameras and a sensor payload, would fly toward an initial target. In conventional seeding operations cloud targets are generally chosen visually by the meteorologist on the ground and/or the pilot in the aircraft (e.g., Keyes et al., 2016; ANSI/ASCE/EWRI, 2017). In the UAS the meteorologist on the ground may not have a visual of the cloud target, and onboard video processing of cloud targets can identify cloudy regions using stereo photogrammetric analysis and automatic feature matching that reconstruct 3D cloud scenes (Romatschke et al., 2017). This information, along with satellite-retrieved cloud droplet effective radius (e.g., Rosenfeld and Lensky, 1998; Woodley et al., 2000; Rosenfeld et al., 2014) can be used to ensure the validity of the radar algorithm. Each UAS would have on-board data processing systems and form a meshed network between them. The UAS would be controlled by a ground station that determines the position of each aircraft system. The UAS1 and UAS2 payload would be lightweight and measure basic thermodynamic properties (i.e., pressure, temperature

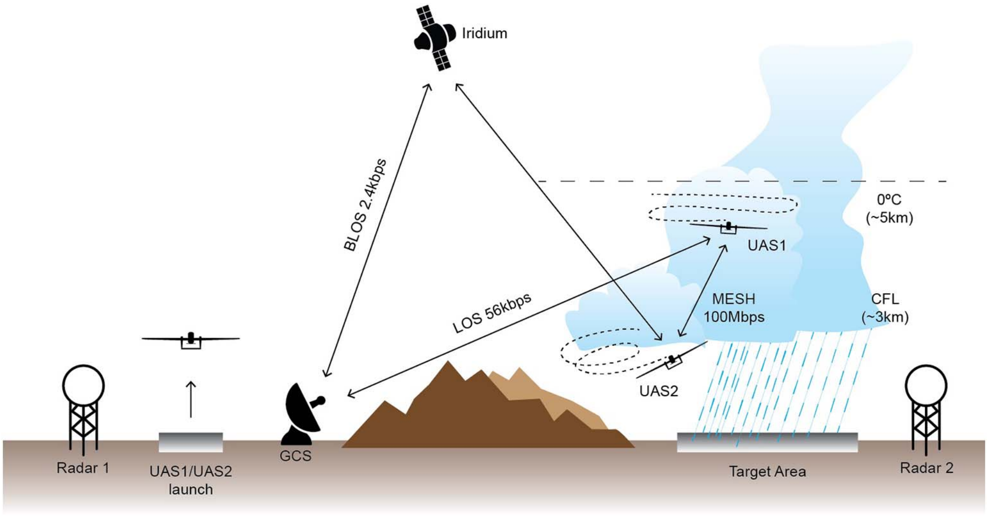

Fig. 1. Schematic diagram of autonomous cloud seeding operations in a target area.

and relative humidity), wind velocity, and aerosol-cloud microphysical properties (i.e., aerosol size distribution and cloud drop size distribution). UAS2 would also be equipped with a seeding apparatus (e.g., hygroscopic flares and/or glaciogenic flares; powders of microparticles or nanoparticles; solutions). The latter seeding apparatus is envisioned to begin as a scaled down version of proven seeding apparatus.

The UAS aircraft could each be a fixed wing aircraft capable of vertical takeoff and landing. UAS1 could typically fly at a higher altitude than UAS2, but in tandem with UAS2, as depicted in Fig. 1. UAS1 makes measurements primarily in-cloud at an altitude above the cloud formation level (CFL) but below the freezing level. The aircraft are controlled by a ground control station (GCS) either through line of site (LOS) or through beyond line of site (BLOS) telemetry. The mesh network between UAS1 and UAS2 is capable of 100 Mbps data rates while line of site operations and beyond line of site are capable of 56 kbps and 2.4 kbps, respectively.

Our framework for integrating autonomous unmanned aircraft systems has three basic developmental components, namely:

1. Algorithms that will use radar and in-situ real-time sensor data to guide the platform toward suitable targets to implement the seeding.
2. Sensors integrated onto UAS platforms that measure meteorological state parameters, wind, turbulence, and aerosol-cloud microphysical properties in conditions that are conducive to seeding of convective clouds.
3. Field tested UAS system that is deployable in a cloud seeding target area.

In this simplest form, the UAS payload would consist of lightweight sensors designed to provide ‘real-time’ in situ-based measurements that support operational flight guidance of the UAS. The flight guidance system would navigate the UAS autonomously to areas of suitable temperature, relative humidity, updraft velocity, aerosol size distribution and droplet size distribution to implement optimal seeding. Optimal seeding means that seeding starts and proceeds at a rate that will yield maximum conversion of cloud water to precipitation that falls in the intended location on the ground, or target area. The ability to have the precipitation fall in an intended area on the ground is known as targeting. Our UAS could be guided by conventional radar to navigate to regions of suitable convection for cloud seeding. The UAS payload, consisting of sensors designed to provide ‘real-time’ in situ-based measurements, will pass temperature, relative humidity, and updraft velocity, for example, into the flight guidance system algorithm supporting the operational flight of the UAS and ensuring optimal autonomous navigation to areas of suitable temperature, relative humidity, and updraft velocity. The measured aerosol size distribution and drop size distribution will provide further guidance to optimize the seeding implementation and targeting of the seeding material. The UAS platform must be capable of supporting the weight of the payload and also handle the turbulence in the atmospheric levels it traverses. UAS platforms that would likely have relevance to cloud seeding activities might be as small as the Manta, which can only carry 6.8 kg of payload compared to the 860 kg of the Global Hawk. Ramana et al. (2007) and Bates et al. (2013) have used a Manta to obtain data in science missions. Axisa and DeFelice (2016) provide additional examples of UAS platforms and their use in atmospheric research. They also make the point that small UAS are not likely capable of carrying some seeding material in the form of ejectable or burn-in-place flares in a quantity deemed practical for weather modification operations. Weather modification operations will most likely require larger UAS, since they likely need to carry sensors, seeding dispenser and material, e.g., AgI acetone solution and/or salt micro-powder, and more (e.g., Table 1). For example, at least $\sim$200 kg of salt micro-powder sized at 1–2 μm is the amount of salt needed for seeding a cloud system (Rosenfeld et al., 2010). Practically, and utilizing commercially available seeding material, a Manta and any UAS with a maximum takeoff weight (MTOW) $<$ 25 kg would not be able to carry any super-micron salt seeding material.

There are many considerations and issues regarding how to equip the UAS with a seeding delivery system that must be considered before this is attempted. Mounting a AgI flare on a UAS and igniting that flare in flight can be done, but using a UAS in an operational program is orders of magnitude more difficult. Conventional technologies used operationally today on manned seeder aircraft are not yet directly transferable to any UAS. A great deal more research and innovation are needed before such can be accomplished. One example is the longevity of flight through supercooled cloud by the UAS. If the supercooled area is extensive, then the UAS might be repositioned, after losing the ice build-up, to seed the cloud top, for example. The UAS must be capable of carrying its instrumentation and a device to hold the seeding material to include seeding delivery for in-cloud and cloud top seeding. Cloud top seeding commonly uses droppable flares, which require approximately 600 to 1800 m, depending on burn time after ignition, before being completely consumed (Keyes et al., 2016). The UAS would have to be able to accommodate such a distance and maintain minimum altitude restrictions as required by regulatory agencies, plus ensure the seeding material reaches the -5 °C vertical cloud level for AgI flares to become active ice nuclei. Conventional seeding aircraft can use AgI flares, among other seeding materials. Successful cloud treatment for precipitation augmentation typically require in-cloud seeding rates of tens to hundreds of grams of AgI per kilometer, and hundreds to

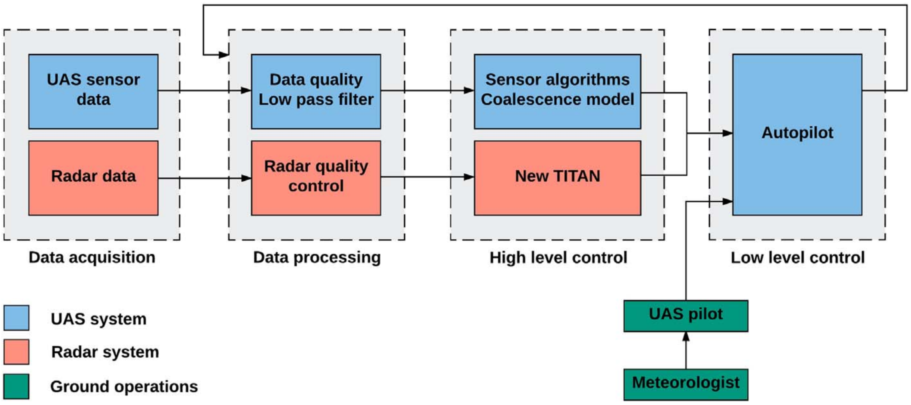

Fig. 2. Autonomous UAS control routine for cloud seeding operations. Sensor and radar data equipped with cloud seeding algorithms provide seeding actions to the UAS. A UAS pilot and meteorologist have the option to modify or interrupt the actions taken by the UAS.
(Adapted from DeFelice and Axisa, 2016).

thousands of grams per hour when seeding the tops of large convective cloud systems (e.g., Keyes et al., 2016). In contrast, the use of AgI solutions from ground-based generators typically yield about 5 to 35 g of AgI per hour of operation (Keyes et al., 2016).

If a UAS used 100 10 g AgI by weight flares with total weight of about 43 g each, the UAS would only carry at least 4.3 kg of extra weight from this component alone. This does not take into account the added weight of the entire dispenser (i.e., flare rack) and other UAS components (e.g. Table 1). The amount of AgI dispensed might yield a sufficient amount of AgI to be successful at enhancing the precipitation efficiency of that cloud system during its flight time. Assuming the operational considerations of the system and the lightweight seeding material delivery were accommodated, how would the seeding material be delivered and reach the appropriate part of the cloud? We can have similar concerns if the seeding material was a powder of nanoparticles/microparticles, or a solution.

Furthermore, if the communication interfaces between each sensor of the seeding payload, and each component of the seeding payload on each platform, data processing functional component, software functional component including autonomous path planning algorithms, are not optimized for a specific UAS and for a specific mission goal or function, then the UAS measurements will be unusable scientifically and will misdirect the flight path resulting in unfavorable results. Trade studies would address the issues related to seeding material, seeding delivery, targeting, sensor placement and non-optimal interfaces with the platform/sensors. The study would investigate sensor performance, on an individual basis and ultimately as a combined unit, as a function of platform integration and placement, for example.

Well established engineering and scientific principles, and lessons-learned from the past decades have to be used in conjunction with this framework and the use of innovative seeding materials based on potential seeding agent technologies (e.g., Luo et al., 2005; Carrasco et al., 2009; Zhang et al., 2009) and delivery technologies (e.g., Hill, 1989, 1990; Hill and Woffinden, 1980). This will ensure optimal and long lasting successful use of each UAS in weather modification or cloud seeding activity. Hence, we caution, that even though small UAS have operated successfully in the vicinity of thunderstorms, and may be technologically capable for possible use to conduct weather modification research and operations, we do not advocate their use without investigating thoroughly the several issues and risks via trade studies for weather modification activities before adopting them.

While we establish and describe the 'boundary conditions' of our evolving framework, the experience of the pilot of these UAS must be high and mentioned. The systems associated with weather modification activities are complex, and we emphasize that the pilot of UAS used for weather modification activities must at least have an equivalent amount of flight time and training as would a pilot for manned aircraft weather modification activities. For the sake of this paper and the discussion, we assume that the UAS is appropriately sized, and optimally configured with respect to each functional mode (Table 1) for each seeding activity. Operational weather modification programs typically use 5 cm weather radar that often have Doppler capability for monitoring precipitation development and storm motion (e.g., with Doppler velocity field) during operations (Keyes et al., 2016; ANSI/ASCE/EWRI, 2017). Radar software for optimal targeting of convective clouds has been developed, and the most common software used is TITAN (Thunderstorm Identification, Tracking, Analysis, and Nowcasting; Dixon and Weiner, 1993). Cloud targeting can be significantly improved by an improved TITAN algorithm. The development of a "new TITAN" algorithm to nowcast the location that is most suitable for seeding, as well as the assimilation of polarimetric Doppler weather radar fields into the new algorithm, would significantly improve current targeting guidance.

The TITAN algorithm could be augmented by 'in situ' UAS sensor data and simple rule-based multi-threshold seed/no seed algorithm. In order to make the algorithm robust, we envision the addition of a coalescence box model that would run on-line on the UAS data system. The box model would ingest the measured drop size distribution and calculate the time evolution of the drop sizes and concentration into the near future. The result would give a very strong indication on whether the cloud is capable of producing drizzle naturally (i.e. without seeding) and hence whether it should be targeted for seeding.

Fig. 2 shows the UAS control routine schematic that is envisioned for autonomous control of the vehicle. Data acquisition would include inputs from the sensors onboard the UAS and the radar covering the target area. Data processing steps ensure that good quality data is passed to the algorithms where high-level control is performed. The new TITAN algorithm would produce the coordinates where seeding conditions are predicted to occur, and pass those locations to the UAS autopilot. Once the UAS is near these coordinates, the sensor algorithms and coalescence model become active and through a hierarchy of logic statements determine the exact location to start seeding.

Our approach will use a simulator implementing software in the loop (SIL) technology to simulate the UAS flight characteristics, UAS payload sensor data and TITAN output. It will be used to optimize the seed/no seed thresholds and targeting algorithm saving the high cost of trial and error approaches and ensuring success. Once the simulations have been completed, field campaigns involving the UAS can be conducted. This approach should provide a smaller number of false positive seeding condition detections.

4. Developing the algorithms that will use radar and in-situ real-time sensor data to guide the platform toward suitable targets to implement the seeding

As discussed in the previous section, the approach toward the development of an autonomous UAS system that detects clouds amenable to seeding and the location of the seeding will require the development of targeting, radar, and sensor algorithms. This can be done by (1) analyzing data from previous field campaigns to define key sensor parameters that input data into the cloud targeting algorithm, and (2) test the performance of these algorithms through SIL based simulator.

4.1. Key sensor parameters for cloud targeting

Large datasets collected during airborne cloud seeding experiments already exist (e.g. Cooper and Lawson, 1984; Krauss et al., 1987; Mather et al., 1997; Bigg, 1997; Cooper et al., 1997; Bruintjes, 1999; Bruintjes et al., 1999, 2001; Caro et al., 2002; Silverman, 2000, 2003; Geerts et al., 2010; Kucera et al., 2010; Rosenfeld et al., 2010; Kulkarni et al., 2012; Posfai et al., 2013;Pokharel et al., 2014; Semeniuk et al., 2014; Geerts et al., 2015; Tas et al., 2015; Pokharel et al., 2016) and provide valuable sources of data to develop and constrain the algorithms that guide the UAS. These data can be mined, analyzed and features extracted to locate representative time-series of key sensors from research aircraft flying at or below cloud base (e.g., sensors that measure updraft velocity, aerosol size distribution and droplet size distribution). Similar analysis would also be conducted on TITAN radar data in regions that are known to be suitable for seeding in order to establish representative radar signatures for the corresponding periods and locations.

The datasets from past campaigns would also be processed so that their output will be similar to that produced by the UAS sensor payload. These data would then be analyzed to develop and constrain the algorithms that guide the UAS, to finalize and test sensor payload algorithms; to perform the data analyses; and to develop the radar algorithm. One example for determining thresholds is the analysis of measured aerosol size distributions, drop size distributions and their relationship to the production of rain. A broad drop size distribution with a tail of large drops might not be suitable for hygroscopic seeding especially if large hygroscopic aerosol particles are present below cloud base. For example, in the Oman mountain region of the UAE it was observed that salts from local pollution modified the aerosol composition and enhanced the concentration of giant cloud condensation nuclei (CCN), and could enhance precipitation (Semeniuk et al., 2014). In Saudi Arabia, it was found that under dusty conditions, a large concentration of coarse-fraction mineral particles was in the aerosol, while under background conditions the aerosol was dominated by submicrometer sulfate particles (Posfai et al., 2013). In background aerosol conditions, the droplets had a narrower drop size distribution (DSD) and were smaller near the base of the cloud than under dusty conditions. These types of clouds can be regarded as having continental properties, with a relatively large number of small droplets that may inhibit the formation of rain. On the other hand, less numerous and larger droplets in the cloud that formed above the dusty boundary layer would favor the natural formation of warm rain.

As an example we consider a research flight in the UAE on 4 September 2002 when cloud droplet and aerosol size distributions measurements were made in a convective cloud over the Habshan oil field in the UAE. Fig. 3 shows aerosol and drop size distribution measurements made inside (blue trace) and below (red trace) cloud base. Cloud base altitude was 3200 m MSL with a temperature of 13 °C. The size distribution spectra are combined measurements from the PCASP[1] instrument and the FSSP[2] instrument. The cloud was penetrated at 300 m above cloud base. The cloud droplet spectrum had a total concentration of 720 cm^{-3}, a mean volume diameter (MVD) and effective radius (ER) of 9.5 and 5.14 μm respectively, a LWC of 0.4 $g\,m^{-3}$, a standard deviation (σ) of 2.8 μm, a mean diameter of 8.6 μm, and a dispersion coefficient of 0.3 (NCAR Research Applications Program, 2003). The aerosol size distribution below cloud base is also shown in Fig. 3.

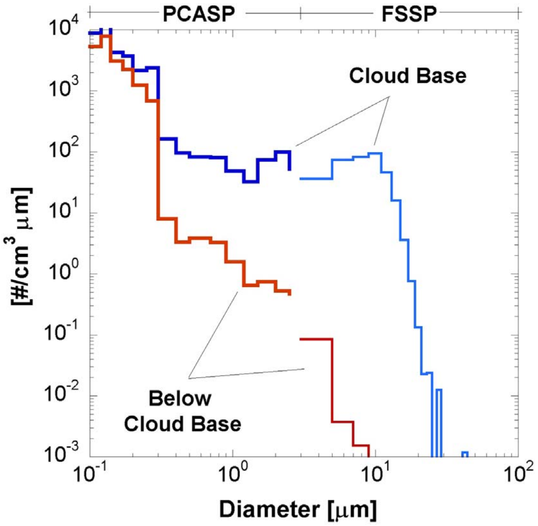

Fig. 3. Cloud droplet and aerosol number distributions in and below cloud base on 4 September 2002 over the Habshan oil field in the UAE.
(Adapted from NCAR Research Applications Program, 2003).

An initial analysis of the moments of the DSD with mean diameter of 8.6 μm and a standard deviation of 2.8 μm may suggest that the cloud is continental microphysically (i.e. a narrow drop size distribution of small drops). In this condition when the cloud base has a continental drop size distribution, hygroscopic seeding would be beneficial (Rosenfeld et al., 2010). However, a more careful look at the FSSP size distribution shows a broader droplet spectra extending to sizes larger than 40 μm diameter. Although this case indicated high droplet concentrations and a mean diameter of small droplets, larger drops were also present, suggesting there was a natural potential for an active coalescence mechanism for precipitation formation. This example merely suggests that a simple threshold analysis of size distributions will not be sufficient to develop robust algorithms. Our approach to developing a cloud targeting algorithm encompasses an analysis process that considers many such cases as well as a rigorous testing of these algorithms. In addition, our approach includes a simple box model that calculates coalescence since such a model can give more accurate information on the activity of the warm rain process.

Part of the targeting algorithm makes use of radar information, but assuming the existence of polarimetric Doppler weather radar data, which is a significant advancement beyond conventional Doppler weather radar guidance, our approach includes the development of a TITAN-based dual polarization algorithm following the NCAR Particle IDentification (PID) algorithm (Vivekanandan et al., 1999) and the exploratory approach of Kucera and Axisa (2016). The advanced technology of polarimetric Doppler radars have several advantages. For example, accuracy in radar-based rain rate estimation is improved by a more detailed description of raindrop size distributions (RDSD). Besides accurate rain rate estimation, spatial variation in RDSD allow better understanding of evaluation of raindrop spectra. Another benefit is the ability to identify hydrometeor types (Doviak and Zrnic, 1993; Straka et al., 2000; Vivekanandan et al., 1999). Those retrievals combined with UAS observations of aerosol and cloud microphysics would enhance the identification success of the most probable regions for cloud seeding targeting in the algorithm development.

---

[1] Passive Cavity Aerosol Spectrometer Probe (PCASP) size range is 0.1 to 3.0μm

[2] Forward Scatter Spectrometer Probe (FSSP) size range is 3 to 47μm

4.2. Cloud targeting algorithm

The complexity of creating autonomy through a hierarchy of algorithms could produce limited functionality and reliability unless it is well designed, simulated and verified. The simulation would include running archived cases in TITAN with a set of assimilated aircraft observable parameters, then performing the simulation to see if the UAS finds the target cloud. Once the target cloud is reached in the simulation, the aircraft would then switch to in-situ sensing and find the area of maximum threshold condition, start seeding at the latter location, then find the position of the minimum threshold condition where seeding stops. The process would repeat for varying dynamic and microphysical conditions until TITAN updates with new target coordinates.

The underlying hypothesis is that TITAN can be modified to not only nowcast the location of convection with real-time radar echo data input about the cloud environment, but also with sensor data input from the UAS. The combination of radar and sensor data would improve the ability to forecast optimal seeding conditions. This would necessitate that (Dixon, personal Communication, 2016):

1) TITAN would need to be improved to handle dual-polarization data. That will provide the ability to identify ZDR columns and regions of high specific differential phase (KDP) between the dual polarization signals, both indicators of significant precipitation. In addition, the NCAR Particle Identification (PID) algorithm (Vivekanandan et al., 1999) could be incorporated and improved, so that TITAN is aware of the microphysical regimes within a storm. The NCAR QPE (Quantitative Precipitation Estimation) is available for the estimation of precipitation rate at the ground, and could be used to verify the algorithm.
2) TITAN would need to be run at two distinct thresholds: (a) high reflectivity threshold (e.g., 35 dBZ) to provide monitoring and nowcasting of existing storms and (b) a low reflectivity threshold (e.g., 20 dBZ) to provide detection of early storm echoes. The high reflectivity threshold instance will provide guidance on convective activity in general. The low reflectivity threshold instance will provide accurate information on storm first echoes. Specific thresholds can be adjusted in the testing process.
3) A TITAN post-processing algorithm would need to be developed to merge the information from the high reflectivity and low reflectivity TITAN instances, and to generate guidance information to the aircraft. The guidance provided will include: (a) vectoring to the initial general location of convective activity; (b) vectoring to new storm first echoes; (c) notification of storm severity, and advice on when to break off from the current target; (d) avoidance of hazardous storm conditions in general; (e) guidance to new locations of interest.
4) The TITAN suite of algorithms already includes applications for the evaluation of seeding cases and these can be utilized to further improve the algorithm.

The simulator implementing SIL would simulate the UAS flight characteristics, with navigation driven by sensor and radar data collected from the previous campaigns. The SIL simulator performance of the combined sensor and radar targeting algorithm would be evaluated by running an ensemble of simulation scenarios. The simulations can be compared to relevant locations from actual flight paths flown on previous cloud seeding missions to understand differences in behaviors between manned operations and that performed by the UAS. This analysis can serve as guidance for improving the algorithm and simulation software.

A simple box model that calculates coalescence, using the measured drop size distribution (DSD) as a starting point, can enhance simulator accuracy. We demonstrate this by using data from a field project called Polarimetric Cloud Analysis and Seeding Test (POLCAST; Kucera et al., 2008; Kucera and Axisa, 2016). In this example, a simple 36-bin box model is used to calculate the evolution of the DSD starting with data ingested from the FSSP onboard a research aircraft. We exemplify the threshold comparison used to support the seeding decision result using POLCAST flight data from 1 July 2008. At least a dozen aircraft penetrations into convective cells were conducted at temperatures ranging from 10.6 to 14.2 °C.

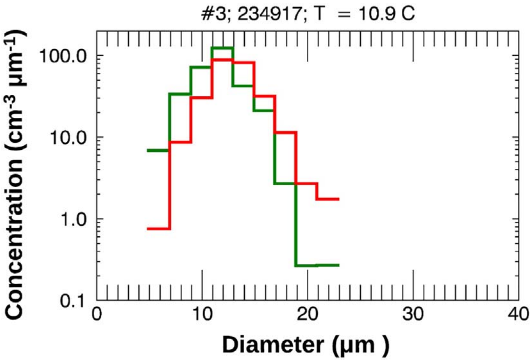

Fig. 4. Ingested drop size distribution (DSD) from penetration number 3 sampled on 1 July 2008. The green trace is the DSD at maximum droplet concentration. The red trace is the DSD with the largest concentration of large droplets.
(Adapted from Kucera and Axisa, 2016).

The measured size distribution (Fig. 4) is ingested into the box model which calculates an ensemble of size distributions (Fig. 5a and b) up to 10 min in the future. These distributions are compared against the metric seeding signature (Fig. 6) to determine if seeding should begin, and/or stop. The distinguishing features of a seeding effect is a DSD featuring an enhanced concentration in the ~15 μm to ~22 μm diameter range due to the "competition effect" as described in Cooper et al. (1997), and a "tail effect" of enhanced concentration of large droplets (~22 μm to ~30 μm diameter range) as described in Rosenfeld et al. (2010). If the comparison matches the seeded metric DSD, an affirmative to begin seeding is passed by the algorithm to the seeding routine. Alternatively, if the number of drizzle drops that are produced by the modeled DSD exceed a certain threshold size and concentration a few minutes into the simulation, that could indicate an active warm rain process and hence no seeding output is passed by the algorithm to the seeding routine. For example, in the instance shown in Fig. 5b, large drops > 30 μm are produced in the box model indicating active warm rain and as such no seeding is recommended. Further, one could estimate the rate of seeding that would be required to modify the measured DSD for a seeding effect and a tail effect. This would benefit operations since it provides guidance for optimal seeding based on actual in situ data and not arbitrary or derived multivariable values.

5. UAS sensor integration and testing

Given the results of our processes to identify sensors (Axisa and DeFelice, 2016) that measure the needed key sensor parameters, our sensor payload could consist of the following instrument suite: an instrument that measures 3D wind velocity such as from a similar device as the Rain Dynamics multi-angle inertial probe (MIP), one that measures drop size distributions such as the Droplet Measurement Technologies (DMT) backscatter cloud probe (BCP; Beswick et al., 2014), one that measures aerosol size distribution such as the Handix Scientific printed optical particle spectrometer (POPS; Gao et al., 2015), and the universal cloud and aerosol sounding system (UCASS) particle spectrometer under development by the University of Hertfordshire. These instruments are listed in Table 2. These sensors are operationally ready, but none have been extensively tested on UAS.

After each instrument is found to perform within specifications, it would be integrated onto the UAS. Inter comparison data obtained from a separate aircraft would enhance the performance comparison. It will

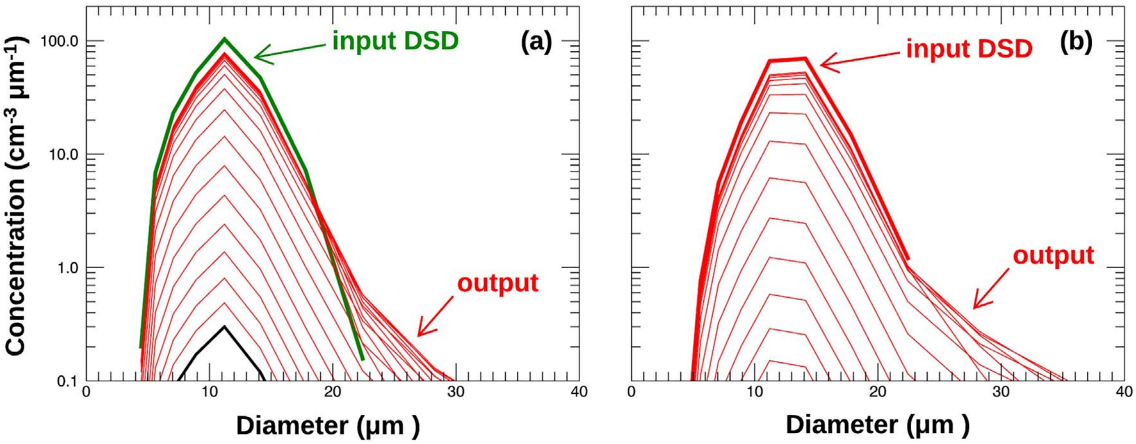

Fig. 5. DSD for penetration number 3 at maximum droplet concentration (a) and at largest concentration of large droplets (b) are used as input to the coalescence model. The model calculations of drop size distributions are printed in red. Notice that the input DSD with large droplets (red trace) produces a tail of large drops > 30 µm in the box model. (Adapted from Kucera and Axisa, 2016).

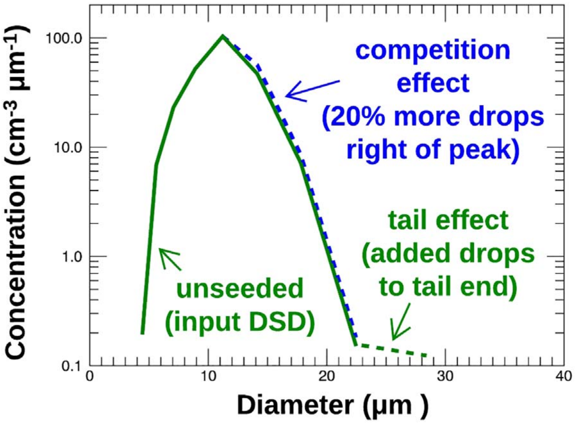

Fig. 6. Metric size distributions from DSD data. The size distributions are the unseeded and seeded metric distribution curves based on measurements and published data. The unseeded distribution is the green solid curve between 4 and 22 µm diameter. The seeded curve is the solid (below 15 µm) modified by the blue dashed curve to 22 µm for the competition effect and the dashed green curve to 29 µm for the tail effect. These seeded curves represent the concept of applying seeding metric spectra.

allow for testing of multiple instruments on different platforms and to constrain instrument errors.

A schematic for the UAS system and subsystem is shown in Fig. 7. It includes the sensor payload with the threshold algorithm application and box model running on the UAS1/UAS2 central processing unit (CPU). The payload data, seeding algorithm data and autopilot data would be transmitted to a ground control station (GCS) via telemetry, with priority given to autopilot data when bandwidth is limited. With this setup UAS1/UAS2 would only need TITAN coordinates uploaded via telemetry to navigate to the preferred location for initial targeting. All other navigation control would be done onboard the vehicle (with pilot over-ride active at all times). The GCS computer would utilize predefined flight plans from mission control software and TITAN position data to generate navigation coordinates for UAS1 and UAS2.

Once the UAS system, subsystem and its components have been tested, the autonomous system would be ready for deployment. We envision a minimum of two deployments, the first would focus on testing the instrumentation on a lightweight UAS and to make sure that the sensors are collecting quality data. The second deployment would be conducted with the sole objective of testing how well the autonomous UAS system performs in an operational cloud seeding program.

6. Testing the system in a cloud seeding application

Once the autonomous system is developed and ready for the second deployment, UAS1 and UAS2, as previously defined, would be programmed to fly in a manner that exploits the advantages of flying in formation (Fig. 8). For example, UAS1 would profile the planetary boundary layer to determine the thermodynamic and aerosol microphysical properties. It would then climb to the 5 °C isotherm while UAS2 would profile downwind of UAS1 and up to the cloud formation level (CFL). Both UAS would fly in formation while approaching the cloud and profile up and down (in a saw tooth type pattern) through the top of the boundary layer while keeping a safe minimum separation of 100 to 300 m. Once near the cloud each UAS would assume their position and commence their seeding mission profile where UAS1 penetrates the cloud and UAS2 samples the cloud updraft and the CFL. Once seeding stops the UAS would loiter for more sampling which may involve a series of cloud penetrations and sampling of aerosols below cloud base (while maintaining separation).

Besides the technological challenges that must be overcome or adequately worked around, the societal and regulatory issues remain and must be respected. Axisa and DeFelice (2016) highlight the latter, but the most immediate issue in this research and development case lies with aviation regulatory limitations (FAA, 2016). In the United States, the Federal Aviation Administration (FAA) is the regulatory entity for air safety from the ground up, whether manned or unmanned, and irrespective of the altitude at which the aircraft is operating. While Axisa and DeFelice (2016) provide details, suffice it to say that in the United States, the FAA (2016) does not provide for UAS to be used for flight in clouds, and certainly not without a certificate of waiver or

Table 2
Lightweight and compact sensors for UAS payload.

Instrument	Measurements	Weight (kg)	Dimensions (mm)
Multi-angle inertial probe (MIP)	Temperature, relative humidity, pressure, 3D wind components (u, v, w)	0.3	240 × 100 × 100
Back scatter cloud probe (BCP)	Drop size distribution (5 to 75 µm)	1.5	117 × 107 × 45
Printed optical particle spectrometer (POPS)	Aerosol size distribution (0.14 to 3 µm)	0.8	170 × 60 × 60
Universal cloud and aerosol sounding system (UCASS)	Particle size distribution (0.3 to 40 µm)	0.28	180 × 64 × 64

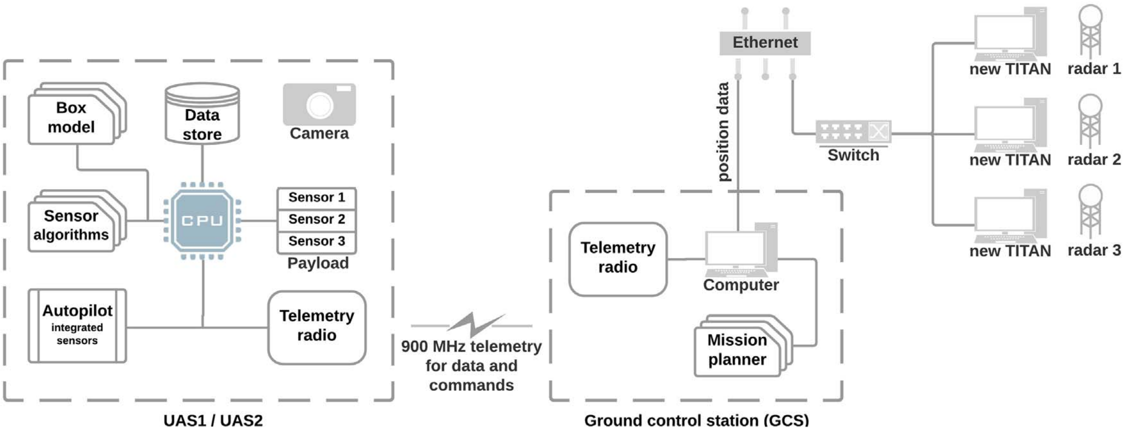

Fig. 7. Schematic for an autonomous UAS system, subsystem and components.

authorization (COA). The COA would at least allow an operator to use a defined block of airspace and includes special provisions unique to a proposed operation, such as, requiring flight under Visual Flight Rules (VFR) only, and/or only during daylight hours. An example of UAS operations with a COA in a cloud environment is the Verification of the Origins of Rotation in Tornadoes Experiment, or VORTEX2, field campaign where a lightweight UAS operated by University of Colorado measured meteorological state parameters and wind below the cloud bases of supercell thunderstorms (Elston et al., 2011).

7. Concluding remarks

In this paper we continue to evolve a conceptual framework for using autonomous and adaptive UAS for cloud seeding operations and evaluation. We introduce for the first time, an engineering-science guided framework to develop UAS technology for integration in future weather modification (cloud seeding) programs with the goal to improve operational efficiency and evaluation accuracy.

A potential paradigm breaking impact lies within evolving improved technology and automation of cloud seeding operations while lowering the operational footprint to optimize the effectiveness and efficiency of cloud seeding programs. Furthermore, besides an improvement in operational cloud seeding operational efficiency and verification, there is plenty of potential from using UAS in tandem, such as an ability to perform simultaneous Eulerian and Lagrangian experiments with cloud, aerosol, and relevant chemical composition measurements on sub-cloud scales (e.g., Axisa and DeFelice, 2016), that might even accelerate the transfer of technology readiness level in instrumentation capable of identifying the chemical composition of single aerosols needed to better understand cloud-aerosol interactions (e.g., DeFelice and Cheng, 1998) and climate change.

The UAS technology we describe could have an impact on the future of rainfall enhancement operations in mountainous regions, arid and semi-arid regions of the world and those countries with limited infrastructure. The sensor package and algorithms can also be used on manned project aircraft to guide the seeding. The data collected from each seeding mission can be used in real-time to improve model parameterizations, and improve processing throughput while maximizing quality by acting as input into coupled models. The latter will also facilitate the development, improvement and/or validation of weather modification-relevant operational and evaluation models, and decision support tools.

Cloud systems associated with weather modification activities are more complex than we conceptualize. Caution must be exercised while pursuing innovation applied to weather modification activities. Even though small UAS may possibly be technologically capable to conduct weather modification research and operations, we do not advocate their use without investigating thoroughly the several issues and risks via

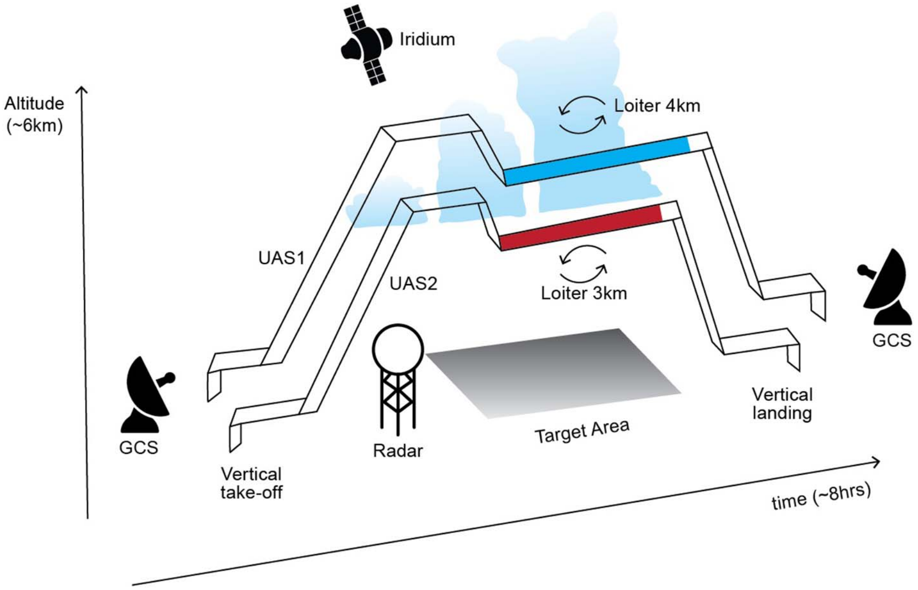

Fig. 8. Example flight profile for UAS1 and UAS2. The shaded blue and red areas indicate the time segment that the UAS are in seeding mode.

trade studies. We also suggest the thorough testing of all UAS, especially from at least mid-sized UAS with 10 kg payload and > 3 h endurance for example, for weather modification activities before adoption. Conventional technologies used operationally today on manned seed aircraft are not directly transferable to any UAS. A great deal more research and innovation are needed before such can be accomplished. Given the latter does occur, the seeding strategy using UAS also needs to be re-examined, since UAS seem less likely to overcome the effects from icing, for example. UAS must be capable of carrying its instrumentation and a delivery system to hold the seeding material. Conventional seeding aircraft can use AgI flares, among other seeding materials, to yield in-cloud seeding rates of tens to hundreds of grams of AgI per kilometer, and hundreds to thousands of grams per hour when seeding the tops of large convective cloud systems (e.g., Keyes et al., 2016). UAS will have to use modern and novel seeding materials that are lightweight and produce more yield in cloud condensation nuclei (CCN) and ice nuclei (IN) per unit weight. Using commercially available seeding material is possible but modifications to how the material is dispensed and packaged is required For example, if a UAS could fly with tens of 10 g droppable flares dropped from a lightweight dispensing system, a UAS could treat several cloud volumes or treat one cloud volume. The amount of AgI dispensed might barely yield a sufficient amount of AgI to be successful at enhancing the precipitation efficiency of that cloud system during its flight time, especially if the AgI aerosol has enhanced nucleation efficiency compared to conventional AgI aerosol. Trade studies investigating these and other seeding system issues, i.e., sensor payload performance and accuracy, are an essential part of successful mission operations. The ultimate operational success lies in ensuring that the UAS pilot at least has the equivalent training and experience as required by a pilot for manned aircraft weather modification activities, and that the program support team are as experienced with cloud seeding programs including those involving UAS.

Finally, the evolving adaptive autonomy of the unmanned aircraft system seeding framework extends beyond improving the cost effective means to optimally conduct and evaluate weather modification activities (in near-real-time), evolve science, technology and engineering disciplines beyond their contemporary levels. It facilitates the capability of enhancing the quality of global lives. This framework extends the infrastructure of more developing countries and countries with limited infrastructure, access to technology that can help provide potable water to their people, and perhaps help minimize social and economic issues.

Acknowledgement

The authors wish to thank the anonymous reviewers for their constructive review comments. The mention of commercial instruments in this paper does not imply endorsement by the authors as the actual performance depends on the application and the system-wide requirements. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

ANSI/ASCE/EWRI, 2013. In: DeFelice, T.P. (Ed.), American National Standards Institute, American Society Civil Engineers, & Environmental Water Resources Institute Standard Practice Guideline for the Design and Operation of Supercooled Fog Dispersal Programs (44–13). ASCE, Reston, VA, USA 38 pp.

ANSI/ASCE/EWRI, 2015. In: Langerud, D. (Ed.), ASCE Standard Practice for the Design and Operation of Hail Suppression Projects (39–15). ASCE, Reston, VA, USA 62 pp.

ANSI/ASCE/EWRI, 2017. In: DeFelice, T.P. (Ed.), ASCE Standard Practice for the Design and Operation of Precipitation Enhancement Projects (42–17). ASCE/EWRI, Reston, VA, USA 52pp.

Axisa, D., 2004. The southern Ogallala aquifer rainfall (SOAR) program—a new precipitation enhancement program in West Texas and Southeastern New Mexico. The Journal of Weather Modification 36 (1), 25–32.

Axisa, D., DeFelice, T.P., 2016. Modern and prospective technologies for weather modification activities: a look at integrating unmanned aircraft systems. Atmos. Res. 178–179, 114–124.

Bates, T.S., Quinn, P.K., Johnson, J.E., Corless, A., Brechtel, F.J., Stalin, S.E., Meinig, C., Burkhart, J.F., 2013. Measurements of atmospheric aerosol vertical distributions above Svalbard, Norway, using unmanned aerial systems (UAS). Atmos. Meas. Tech. 6, 2115–2120. http://dx.doi.org/10.5194/amt-6-2115-2013.

Bergeron, T., 1935. "On the Physics of Clouds and Precipitation." Proc., 5th Assembly IUGG, IUGG, (Lisbon, 1933). pp. 156–178.

Berthet, C., Wesolek, E., Dessens, J., Sanchez, J.L., 2013. Extreme hail day climatology in Southwestern France. Atmos. Res. 123, 139–150.

Beswick, K., Baumgardner, D., Gallagher, M., Volz-Thomas, A., Nedelec, P., Wang, K.-Y., Lance, S., 2014. The backscatter cloud probe — a compact low-profile autonomous optical spectrometer. Atmos. Meas. Tech. 7, 1443–1457. http://dx.doi.org/10.5194/amt-7-1443-2014.

Bigg, E.K., 1997. An independent evaluation of a South African hygroscopic cloud seeding experiment, 1991–1995. Atmos. Res. 43, 111–127.

Blunden, J., Arndt, D.S. (Eds.), 2016. State of the Climate in 2015. Bull. Amer. Meteor. Soc. 97(8). pp. S1–S275. http://dx.doi.org/10.1175/2016BAMSStateoftheClimate.1. http://www.ametsoc.net/sotc/StateoftheClimate2015_lowres.pdf.

Braun, S.A., Kakar, R., Zipser, E., Heymsfield, G., Albers, C., Brown, S., Durden, S.L., Guimond, S., Halverson, J., Heymsfield, A., Ismail, S., 2013. NASA's genesis and rapid intensification processes (GRIP) field experiment. Bull. Am. Meteorol. Soc. 94 (3), 345–363.

Bruintjes, R.T., 1999. A review of cloud seeding experiments to enhance precipitation and some new prospects. Bull. Amer. Meteor. Soc. 80, 805–820.

Bruintjes, R.T., Breed, D., Dixon, M.J., Brown, B.G., Salazar, V., Rodriguez, H.R., 1999. Program for the Augmentation of Rainfall in Coahuila (PARC): Overview and Preliminary Results. Preprints 14th Conf. On Planned and Inadvertent Weather Modification, Everett WA. pp. 600–603.

Bruintjes, R.T., Breed, D., Salazar, V., Dixon, M., Kane, T., Foote, G.B., Brown, B., 2001. Overview and results from the Mexican hygroscopic seeding experiment. In: Preprints, AMS Symposium on Planned and Inadvertent Weather Modification, Albuquerque NM, .

Caro, D., Wobrock, W., Flossmann, A.I., 2002. A numerical study on the impact of hygroscopic seeding on the development of cloud particle spectra. J. Appl. Meteorol. 41, 333–350.

Carrasco, J., Michaelides, A., Forster, M., Haq, S., Raval, R., Hodgson, A., 2009. A one-dimensional ice structure built from pentagons. Nat. Mater. 8 (5), 427–431.

Cook, B.I., Ault, T.R., Smerdon, J.E., 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Sci. Adv. 1, e1400082 7 pp. http://dx.doi.org/10.1126/sciadv.1400082.

Cooper, W.A., Lawson, R.P., 1984. Physical interpretation of results from the HIPLEX-1 experiment. J. Climate Appl. Meteor. 23, 523–540.

Cooper, W.A., Bruintjes, R.T., Mather, G.K., 1997. Calculations pertaining to hygroscopic seeding with flares. J. Appl. Meteorol. 36, 1449–1469.

DeFelice, T.P., Axisa, D., 2016. Developing the framework for integrating autonomous unmanned aircraft systems into cloud seeding activities. J. Aeronautics & Aerospace Engineering 5 (172), 001–006. http://dx.doi.org/10.4172/2168-9792.1000172. www.omicsgroup.org/journals/ArchiveJAAE/currentissue-aeronautics-aerospace-engineering-open-access.php.

DeFelice, T.P., Cheng, R.G., 1998. On the phenomenon of nuclei enhancement during the evaporative stage of cloud. Atmos. Res. 47 (8), 15–40.

DeFelice, T.P., Golden, J., Griffith, D., Woodley, W., Rosenfeld, D., Breed, D., Solak, M., Boe, B., 2014. Extra area effects of cloud seeding-an updated assessment. Atmos. Res. 135–6, 193–203.

Dennis, A.S., 1980. Weather Modification by Cloud Seeding. Academic Press, New York.

Dessens, J., Berthet, C., Sanchez, J.L., 2009. Seeding optimization for hail prevention with ground generators. J. Weather Modif. 41, 104–111.

Dessens, J., Berthet, C., Sanchez, J.L., 2015. Change in hailstone size distributions with an increase in the melting level height. Atmos. Res. 158-9, 245–253. http://dx.doi.org/10.1016/j.atmosres.2014.07.004.

Dixon, M., Weiner, G., 1993. TITAN: thunderstorm identification, tracking, analysis, and nowcasting — a radar-based methodology. J. Atmos. Ocean. Technol. 10, 785–797.

Doviak, R.J., Zrnic, D.S., 1993. Doppler Radar and Weather Observations. Academic Press, New York 562 pp.

Dydek, Z.T., Annaswamy, A.M., Lavretsky, E., 2013. Adaptive control of quadrotor UAVs: a design trade study with flight evaluations. IEEE Trans. Control Syst. Technol. 21 (4), 1400–1406. http://dx.doi.org/10.1109/TCST.2012.2200104.

Elliott, R.D., 1986. "Review of wintertime orographic cloud seeding." Precipitation enhancement-A scientific challenge. In: Braham Jr.R.R. (Ed.), Meteor. Monogr. 21(43). AMS, Boston, pp. 87–103.

Elston, J.S., Roadman, J., Stachura, M., Argrow, B., Houston, A., Frew, E., 2011. The tempest unmanned aircraft system for in situ observations of tornadic supercells: design and VORTEX2 flight results. Journal of Field Robotics 28 (4), 461–483.

Emmitt, G.D., Godwin, K., Greco, S., 2014. Mountain Waves and Energy Harvesting for UAVs using a DWL. Working Group Meeting on Space-based Lidar Winds at Boulder CO, May 13–14. https://swa.com/images/LidarAirborne/LWG2014_Emmitt_Godwin_Greco_AEORA.pdf Accessed 02/16/17.

FAA, 2016. Unmanned Aircraft Systems. http://www.faa.gov/uas/ accessed 02.17.17.

Fahey, D.W., Churnside, J.H., Elkins, J.W., Gasiewski, A.J., Rosenlof, K.H., Summers, S., Aslaksen, M., Jacobs, T.A., Sellars, J.D., Jennison, C.D., Freudinger, L.C., 2006. Altair unmanned aircraft system achieves demonstration goals. EOS Trans. Am. Geophys. Union 87 (20), 197–201.

Ficklin, D.L., Maxwell, J.T., Letsinger, S.L., Gholizadeh, H., 2015. A climatic deconstruction of recent drought trends in the United States. Environ. Res. Lett. 10, 044009. 10pp. http://dx.doi.org/10.1088/1748-9326/10/4/044009.

Findeisen, 1938. Die kolloidmeteorologischen vorgange bei der niederschlagsbildung. Meteor. Z. 55, 121–131.

Frew, E.W., Elston, J., Argrow, B., Houston, A.L., Rasmussen, E.N., 2012. Unmanned aircraft systems for sampling severe local storms and related phenomena. IEEE Robot. Autom. Mag. 19 (85–95), 2012.

Gao, R.S., Telg, H., McLaughlin, R.J., Ciciora, S.J., Watts, L.A., Richardson, M.S., Schwarz, J.P., Perring, A.E., Thornberry, T.D., Rollins, A.W., Markovi, M.Z., Bates, T.S., Johnson, J.E., Fahey, D.W., 2015. A light-weight, high-sensitivity particle spectrometer for PM2.5 aerosol measurements. Aerosol Sci. Technol. http://dx.doi.org/10.1080/02786826.2015.1131809.

Geerts, B., Miao, Q., Yang, Y., Rasmussen, R., Breed, D., 2010. An airborne profiling radar study of the impact of glaciogenic cloud seeding on snowfall from winter orographic clouds. J. Atmos. Sci. 67, 3286–3302.

Geerts, B., Yang, Y., Rasmussen, R., Haimov, S., Pokharel, B., 2015. Snow growth and transport patterns in orographic storms as estimated from airborne vertical-plane dual-Doppler radar data. Mon. Weather Rev. 143, 644–665.

Gupta, S.G., Ghonge, M.M., Jawandhiya, P.M., 2013. Review of unmanned aircraft system (UAS). Int. J. Adv. Res. Comput. Eng. Technol. 2 (4), 1646–1658.

Hill, G.E., 1989. Laboratory calibration of a vibrating wire device for measuring concentrations of supercooled liquid water. J. Atmos. Ocean. Technol. 6 (6), 961–970.

Hill, G.E., 1990. Radiosonde Supercooled Liquid Water Detector. Final Report Delivered in September to U.S. Cold Regions Research & Engineering Lab., Hanover, NH for Contract DACA 89–84-C-0005. Atek Data Corp, 2300 Canyon Blvd., Boulder, CO 80302 97 pp.

Hill, G.E., Woffinden, D.S., 1980. A balloon-borne instrument for the measurement of vertical profiles of supercooled liquid water concentration. J. Appl. Meteorol. 19, 1285–1292.

Hoff, R.M., Hardesty, R.M., Carr, F., Weckwerth, T., Koch, S., Benedetti, A., Crewell, S., Cimini, D., Turner, D., Feltz, W., Demoz, B., Wulfmeyer, V., Sisterson, D., Ackerman, T., Fabry, F., Knupp, K., 2012. Thermodynamic Profiling Technologies Workshop report to the National Science Foundation and the National Weather Service. NCAR Technical Note NCAR/TN-488 + STR, 80 pp, 2012 .

Hood, R., 2014. NOAA Unmanned Aircraft Systems (UAS) Program Activities, 28 May 2014. http://uas.noaa.gov/library/presentations/NOAA-UAS-Program-Brief28May14.pdf accessed 02.16.17.

Jensen, E.J., Pfister, L., Jordan, D.E., Bui, T.V., Ueyama, R., Singh, H.B., Thornberry, T., Rollins, A.W., Gao, R.S., Fahey, D.W., Rosenlof, K.H., et al., 2017. The NASA airborne tropical TRopopause EXperiment (ATTREX): high-altitude aircraft measurements in the tropical Western Pacific. Bull. Am. Meteorol. Soc. 98 (1), 129–143.

Keyes, C.G., Bomar, G.W., DeFelice, T.P., Griffith, D.A., Langerud, D.W., 2016. Guidelines for cloud seeding to augment precipitation. In: ASCE Manuals and Reports on Engineering Practice NO. 81, third ed. ASCE, Reston, VA., USA 234 pp.

Krauss, T.W., Bruintjes, R.T., Verlinde, J., Kahn, A., 1987. Microphysical and radar observations of seeded and unseeded continental cumulus clouds. J. Climate Appl. Meteor. 26, 585–606.

Kucera, P.A., Axisa, D., 2016. Polarimetric Cloud Analysis and Seeding Test Evaluation Study: Final Report. North Dakota Atmospheric Resource Board.

Kucera, P.A., Theisen, A., Langerud, D., 2008. Polarimetric cloud analysis and seeding test (POLCAST). J. Weather Mod. 40, 64–76.

Kucera, P.A., Axisa, D., Burger, R.P., Collins, D.R., Li, R., Chapman, M., Posada, R., Krauss, T.W., Ghulam, A.S., 2010. Features of the weather modification assessment project in the southwest region of Saudi Arabia. J. Wea. Mod. 42, 78–103.

Kulkarni, J.R., Maheshkumar, R.S., Morwal, S.B., Padma Kumari, B., Konwar, M., Deshpande, C.G., Joshi, R.R., Bhalwankar, R.V., Pandithurai, G., Safai, P.D., Narkhedkar, S.G., Dani, K.K., Nath, A., Sathy, Nair, Sapre, V.V., Puranik, P.V., Kandalgaonkar, S.S., Mujumdar, V.R., Khaladkar, R.M., Vijaykumar, R., Prabha, T.V., Goswami, B.N., 2012. The cloud aerosol interaction and precipitation enhancement experiment (CAIPEEX): overview and preliminary results. Curr. Sci. 102 (2012), 413–425.

Loegering, G., 2002. "Global Hawk — A New Tool for Airborne Atmospheric Sensing", 1st UAV Conference and Workshop on Unmanned Aerospace Vehicles, S, 20–23 May 2002, Portsmouth, Virginia, AIAA. http://dx.doi.org/10.2514/6.2002-3458. http://arc.aiaa.org/doi/abs/10.2514/6.2002-3458.

Luo, Y.G., Zou, L., Hu, E., 2005. A comparative study on preparation of TiO2 pellets as photocatalysts based on different precursors. Mater. Sci. Forum 475-479, 4165–4170.

MacDonald, A.E., 2005. A global profiling system for improved weather and climate prediction. Bull. Am. Meteorol. Soc. 86, 1747–1764.

Marwitz, J., 1986. In: Braham Jr.R.R. (Ed.), "A Comparison of Winter Orographic Storms Over the San Juan Mountains and the Sierra Nevada." Precipitation Enhancement—A Scientific Challenge. Meteorol. Monogr. 21(43). AMS, Boston, pp. 109–113.

Mather, G.K., Terblanche, D.E., Steffens, F.E., Fletcher, L., 1997. Results of the South African cloud-seeding experiments using hygroscopic flares. J. Appl. Meteorol. 36, 1433–1447.

McNutt, M., 2014. The drought you can't see. Science 345 (6204), 1543–1643.

NCAR Research Applications Program, 2003. Rainfall Enhancement and Air Chemistry Studies. In: United Arab Emirates, 2001–2002 Final Report (470 pp.). United Arab Emirates: Department for Water Resources Studies The Office of His Highness the President.

Newman, P.A., Fahey, D.W., 2010. The Global Hawk Pacific Mission (April–May, 2010). AGU Annual Mtg., San Francisco, CA 13–17 December.

NRC, 2009. Observing Weather and Climate From the Ground Up: A Nationwide Network of Networks. The National Academies Press, Washington, DC, pp. 2009.

Pokharel, B., Geerts, B., Jing, X., Friedrich, K., Aikins, J., Breed, D., Rasmussen, R., Huggins, A., 2014. The impact of ground-based glaciogenic seeding on clouds and precipitation over mountains: a multi-sensor case study of shallow precipitating orographic cumuli. Atmos. Res. 147-148, 162–182. http://dx.doi.org/10.1016/j.atmosres.2014.05.014.

Pokharel, B., Geerts, B., Jing, X., Friedrich, K., Ikeda, K., Rasmussen, R., 2016. A multi-sensor study of the impact of ground-based glaciogenic seeding on clouds and precipitation over mountains in Wyoming. Part II: seeding impact analysis. Atmos. Res. 183, 42–57. http://dx.doi.org/10.1016/j.atmosres.2016.08.018.

Posfai, M., Axisa, D., Tompa, E., Freney, E., Bruintjes, R., Buseck, P., 2013. Interactions of mineral dust with pollution and clouds: an individual-particle TEM study of atmospheric aerosol from Saudi Arabia. Atmos. Res. 122, 347–361.

Ramana, M.V., Ramanathan, V., Kim, D., Roberts, G.C., Corrigan, C.E., 2007. Albedo, atmospheric solar absorption and heating rate measurements with stacked UAVs. Q. J. R. Meteorol. Soc. 133, 1913–1931. http://dx.doi.org/10.1002/qj.172.

Romatschke, U., Grubišić, V., Zehnder, J.A., 2017. In: Photogrammetric Analysis of Rotor Clouds Observed during T-REX. 97th American Meteorological Society Annual Meeting, Robert A. Houze, Jr. Symposium, #443. AMS, Boston. https://ams.confex.com/ams/97Annual/webprogram/Paper305719.html.

Rosenfeld, D., Lensky, I.M., 1998. Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. Bull. Am. Meteorol. Soc. 79 (11), 2457–2476.

Rosenfeld, D., Axisa, D., Woodley, W.L., Lahav, R., 2010. A quest for effective hygroscopic cloud seeding. J. Appl. Meteorol. Climatol. 49 (7), 1548–1562.

Rosenfeld, D., Liu, G., Yu, X., Zhu, Y., Dai, J., Xu, X., Yue, Z., 2014. High-resolution (375 m) cloud microstructure as seen from the NPP/VIIRS satellite imagery. Atmos. Chem. Phys. 14 (5), 2479–2496.

Schaefer, V.J., 1946. The production of ice crystals in a cloud of supercooled water droplets. Science 104 (2707), 459.

Scheve, T., 2008. How the MQ-9 Reaper Works. http://science.howstuffworks.com/reaper.htm accessed 02.16.17.

Semeniuk, T.A., Bruintjes, R.T., Salazar, V., Breed, D.W., Jensen, T.L., Buseck, P.R., 2014. Individual aerosol particles in ambient and updraft conditions below convective cloud bases in the Oman mountain region. J. Geophys. Res. 119, 2511–2528.

Silverman, B.A., 2000. An independent statistical evaluation of the South African hygroscopic flare seeding experiment. J. Appl. Meteorol. 39, 1373–1378.

Silverman, B.A., 2003. A critical assessment of hygroscopic seeding of convective clouds for rainfall enhancement. Bull. Amer. Meteor. Soc. 84, 1219–1230.

Silverman, B.A., Rosenfeld, D., Sukarnjanaset, W., Talumassawatdi, R., 1999. "The Thailand Warm Cloud Seeding Experiment: 2, Results of the Statistical Evaluation." Prepr., 7th WMO Scientific Conf. on Wea. Modif., WMO, Geneva. pp. 9–12.

Sippel, J.A., Zhang, F., Weng, Y., Tian, L., Heymsfield, G.M., Braun, S.A., 2014. Ensemble Kalman filter assimilation of HIWRAP observations of hurricane Karl (2010) from the unmanned global hawk aircraft. Mon. Weather Rev. 142, 4559–4580.

Straka, J.M., Zrnic, D.S., Ryzhkov, A.V., 2000. Bulk hydrometeor classification and quantification using polarimetric radar data: synthesis of relations. JAMA 39, 1341–1372.

Tas, E., Teller, A., Altaratz, O., Axisa, D., Bruintjes, R., Levin, Z., Koren, I., 2015. The relative dispersion of cloud droplets: its robustness with respect to key cloud properties. Atmos. Chem. Phys. 15, 2009–2017. http://dx.doi.org/10.5194/acp-15-2009-2015.

Vivekanandan, J., Zrnic, D.S., Ellis, S.M., Oye, R., Ryzhkov, A.V., Straka, J., 1999. Cloud microphysics retrieval using s-band dual-polarization radar measurements. BAMS 80, 381–388.

Vonnegut, B., 1947. The nucleation of ice formation by silver iodide. J. Appl. Phys. 18, 593–595.

Vonnegut, B., 1981. Misconception about cloud seeding with dry ice. JWM 13, 9–10.

Warburton, J.A., Young, L.G., Stone, R.H., 1995. Assessment of seeding effects in snowpack augmentation programs: ice nucleation and scavenging of seeding aerosols. J. Appl. Meteorol. 34, 121–130.

Woodley, W.L., Rosenfeld, D., 2004. The development and testing of a new method to evaluate the operational cloud-seeding programs in Texas. J. Appl. Meteorol. 43, 249–263.

Woodley, W.L., Rosenfeld, D., Strautins, A., 2000. Identification of a seeding signature in Texas using multi-spectral satellite imagery. The Journal of Weather Modification 32 (1), 37–52.

Woodley, W.L., Rosenfeld, D., Silverman, B.A., 2003a. Results of on-top glaciogenic cloud seeding in Thailand. Part I: the demonstration experiment. J. Appl. Meteorol. 42, 920–938.

Woodley, W.L., Rosenfeld, D., Silverman, B.A., 2003b. Results of on-top glaciogenic cloud seeding in Thailand. Part II: exploratory analyses. J. Appl. Meteorol. 42, 939–951.

Zhang, W., Zou, L., Wang, L., 2009. Photocatalytic TiO 2/adsorbent nanocomposites prepared via wet chemical impregnation for wastewater treatment: a review. Appl. Catal. A Gen. 371 (1–2), 1–9.

Zhao, T., Dai, A., 2015. The magnitude and causes of global drought changes in the twenty-first century under a low–moderate emissions scenario. J. Clim. 28, 4490–4512. http://dx.doi.org/10.1175/JCLI-D-14-00363.1.