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Invited review article

Modern and prospective technologies for weather modification activities: A look at integrating unmanned aircraft systems

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ABSTRACT

Present-day weather modification technologies are scientifically based and have made controlled technological advances since the late 1990s, early 2000s. The technological advances directly related to weather modification have primarily been in the decision support and evaluation based software and modeling areas. However, there have been some technological advances in other fields that might now be advanced enough to start considering their usefulness for improving weather modification operational efficiency and evaluation accuracy. We consider the programmatic aspects underlying the development of new technologies for use in weather modification activities, identifying their potential benefits and limitations. We provide context and initial guidance for operators that might integrate unmanned aircraft systems technology in future weather modification operations.

Contents

1. Introduction

This review paper discusses new technologies and techniques that are nearly ready for beneficial use during operational weather modification activities with a particular focus on the integration of unmanned aircraft systems (UAS) or unmanned aerial vehicles (UAVs) into weather modification programs. It is the objective of this review to provide some basic context and initial guidance for operators that might integrate UAS technology in future weather modification operations. UAS with simple payloads can measure meteorological state parameters, wind and turbulence and other variables in conditions that are conducive to seeding to improve, validate and monitor operational weather modification activities. Weather modification technologies may be effectively applied (e.g., ASCE/EWRI, 2016; ANSI/ASCE/EWRI, 2013, 2015) to facilitate the water and energy cycles, which are key to dealing with many present and potential future scientific, environmental, and socioeconomic issues. It has been predicted that more than 40% of the world's population will live in water-stressed areas by the decade of the 2020s (DeFelice, 2002). McNutt (2014) reported that the western

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hemisphere is in the midst of a significant drought, with millions in danger of starvation. Hence the need to develop the science and technology that improve the appropriate systems used to monitor and manage atmospheric water should remain at the forefront of current research. Better technologies will mean more water returned to the surface in the form of precipitation. More precipitation will help resolve the direct and indirect issues related to drought. This does not undermine the need for other technologies to deal with other aspects of this complex issue.

Limited advances have been made in the development of present-day weather modification (cloud seeding) technologies and the ability to recognize treatable clouds. While, for example, Bruintjes (1999) was focused on the science status, DeFelice (2002) outlined a high-level national program plan for developing modern weather modification science and technologies. Golden and DeFelice (2006) had provided additional rationale and guidelines for implementing what DeFelice (2002) laid out. The DeFelice (2002) and Golden and DeFelice (2006) contributions collectively produced a high-level comprehensive research and development framework for identifying relevant, conventional and non-conventional, practical, innovative technologies. The functional components of the a-priori framework with the greatest need for advanced technology and technique development fall into the following general areas:

a. Cloud seeding activity monitoring and simulation;
b. Seeding agent delivery and dispersion;
c. Cloud seeding evaluation technology, techniques and protocols.

Advancements made in ground based seeding agent delivery systems and techniques are limited at best and not discussed here. Dessens et al. (2016) review hail suppression by ground seeding, focusing on the production of silver iodide (AgI) nuclei, their dispersion, and measurements in the atmosphere, as well as their observed or simulated effects. In winter orographic cloud seeding, advancements in numerical modeling have been used for operational and evaluation considerations (e.g., Xue et al., 2013; Xue et al., 2014) and more can be done with developing observational techniques to validate and improve such models. More representative measurements will enhance the characterization of the dynamical and physico-chemical properties of seeding agent dispersion and delivery to treatable clouds. Such measurements would be designed to also improve aerosol-nucleation, microphysical and hydro-meteorological routines and their interfaces. They are sparse and costly to make but will reduce computational noise from the combined routines, and maximize the accuracy of the algorithm outputs. Inaccurate representation of particle dispersion and transport may lead to misleading operational and evaluation statistical results. Technology advancement is needed in monitoring cloud seeding activity, seeding agent delivery and effectiveness, as well as evaluation technology. All these components would benefit from the widespread deployment of cost effective atmospheric sensing platforms.

2. Technology advancements

In this section, we highlight some of the more promising, recent, relevant technological advancements that might improve weather modification operations, the prominent risks, issues and concerns involved, and the benefits from their use. We followed a general process (Fig. 1) to identify technologies and techniques that might be potentially useful to modern cloud seeding activities.

The process starts with a comprehensive literature search to save time and effort in the long term, and minimize the 'reinvention of the wheel'. For example, literature search should be done to identify candidate technologies/techniques potentially useful for cloud seeding activities. Had this step alone been conducted, most, if not all, of the proposed geoengineering techniques would have been dismissed. The next steps are to explore possibilities of implementing the candidate techniques and to conduct cost–benefit analyses. If the costs are comparable to those associated with using conventional cloud seeding techniques, the benefit to cost ratio is high. If technology/technique is practical to create and use, then experts should be consulted. If the technology is impractical, the process should start from the beginning. In each case expert feedback should be considered. Periodic reviews by experts, incorporating review results, and documenting results are expected. A scientifically based model should be used to optimize the candidate technology/technique, its components and vulnerability. This step assumes the scientifically based model consistently yields representative, real results for known operational conditions. If this step does not change the technology/technique, field-testing commences. If the technology changes another cost benefit analysis is required. Once field-testing is complete, the resulting technology/technique is deployed in an operational setting to determine its robustness.

2.1. Identifying technology advancements

We focused on identifying which technology and/or technique were/was nearly at a technology readiness level (TRL) that was useful to weather modification activities with minimal, if any, research and development toward making each technology or technique operationally

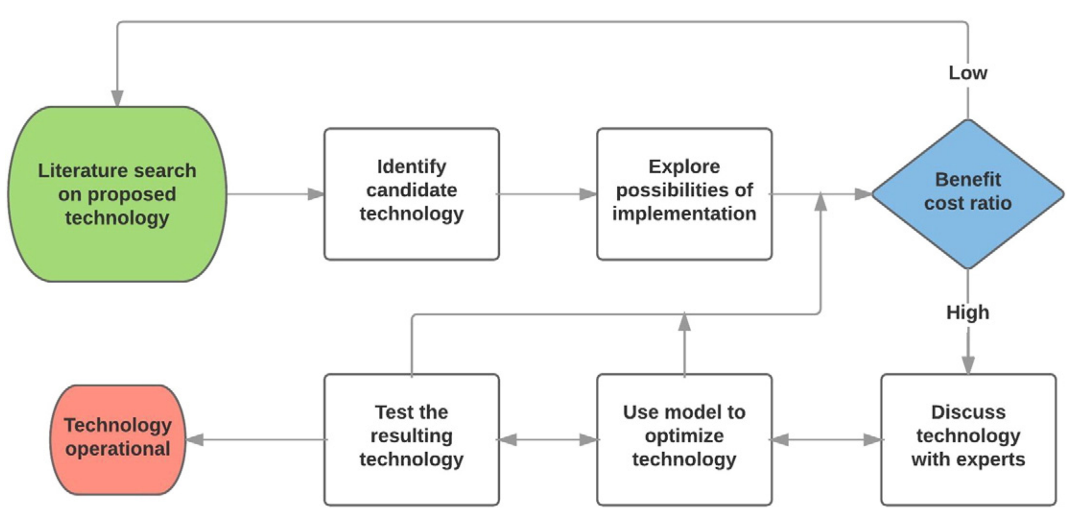

Fig. 1. General process used to identify a useful technology/technique.

viable. For the purpose of this review, technology is considered ready for operations once it has progressed beyond the prototype level. That is, technology has been proven to work in its final form and under expected conditions. In nearly all cases, this corresponds to the completion of true system development. Examples include, developmental test and evaluation of the system to determine if it meets design specifications. Documentation includes the results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate, and an assessment of whether it will meet its operational requirements. It will also include, challenges, if any, that were encountered.

In the case of software, the corresponding readiness level (or software readiness level, SRL) is a software package that has been demonstrated to work in its final form and under expected conditions. A software package contains at a minimum: the model, data cube used for development and for testing, as well as documentation of the model, data, readiness and in-process reviews and tests. A software package is ready for operations when it is demonstrated through successful (operational) mission-proven capabilities that require minimal further development. Such a software package will readily produce repeatable and reusable absolute results. All software documentation (e.g., theoretical basis, detailed design, interface and configuration management, data dictionary, maintenance plan) should have been verified.

We found many interesting technologies, most of which were not applicable, or could not conceivably be useful to any weather modification application. Examples of technologies and techniques that would not be useful to weather modification include: (i) a high-powered laser to create a cloud (Rohwetter et al., 2010), (ii) hail cannons to disrupt the formation of hailstones (Ollivier, 1995), and (iii) ionization generators to increase cloud condensation nuclei (CCN) and presumably rainfall by ion generation (Doshi and Agashe, 2014). These technologies have proven unsuccessful in showing any feasibility of producing the desired effect in the real atmosphere. In addition, geoengineering technologies and techniques such as the albedo method for reversing global warming (Salter et al., 2008), or, using large aircraft "super tankers" to airdrop water-absorbing powder onto hurricanes (Behar, 2005), or reducing the destruction of hurricanes by steering them and using a mono-layer of acetyl alcohol to retard water vapor flux feeding hurricanes (e.g., Hoffman, 2004; Emanuel, 2005 personal communication) have yet to be tested. Cotton (2009) provides additional details on geoengineering technologies and techniques. Such methods, besides being highly expensive and impractical to apply, need additional decades of development before they may be considered cost effective to apply. Most geoengineering ideas are variants of near century old ideas that were similarly shown to be impractical by the middle 1900s. Even the non-geoengineering method proposed by Rosenfeld et al. (2007) to reduce the destructiveness of hurricanes using submicron hygroscopic aerosols needs further development.

Technologies that continue to apply and evaluate the hypothesis of glaciogenic seeding by AgI particles have demonstrated operational feasibility. It has been fairly well established that AgI is an effective seeding agent when applied in supercooled clouds (e.g., Deshler and Reynolds, 1990). The nucleation of AgI has also been tested in cloud chambers. In the past the Colorado State University (CSU) dynamic cloud chamber has been used to examine the ice nucleating properties of AgI aerosols held at water saturation (DeMott et al., 1983). When the CSU cloud chamber stopped operating, experiments to investigate nucleation activity of AgI aerosols ceased, despite the emergence of more sophisticated chambers that perform ice nucleation experiments (e.g., AIDA aerosol and cloud chamber facility; Möhler et al., 2003). In supercooled convective clouds it has been observed that AgI seeding at cloud tops produces large increases in ice particle concentrations, decreases in liquid water contents, and increases in precipitation hydrometeors lower down in the clouds (e.g., Hobbs and Politovich, 1980; English and Marwitz, 1981). In a more recent study that investigates the impact of ground-based AgI seeding on shallow, lightly precipitating winter orographic cumuli observed during the AgI Seeding Cloud Impact Investigation (ASCII) experiment in Wyoming, particle probes onboard the research aircraft show that the concentration of small ice crystals was significantly larger downwind of the AgI generators during seeding, suggesting that AgI seeding increased the concentration of ice crystals in shallow convection (Pokharel et al., 2014).

In the case of warm clouds, one could conceptualize that hygroscopic seeding with optimally sized particles could produce drizzle drops that lead to more rainfall. Operationally the main challenge with seeding warm clouds has been with the physical and chemical properties of the seeding agent and delivery by means of aircraft. The issue of seeding effectively with salt of optimal size and concentration has been the focus of several modeling studies (e.g., Cooper et al., 1997; Yin et al., 2000; Yin et al., 2001; Caro et al., 2002; Segal et al., 2004; Kuba and Murakami, 2010; Drofa et al., 2010). It was found that there exists an optimum radius of seeding particles from 1.5 μm to 2.5 μm that provided the maximum raindrop production from a given mass of the seeding agent. It was also found that hygroscopic flares were less efficient in raindrop production. The smaller efficiency of the flares was related to the presence of a large concentration of small ~0.2 μm radii CCN that were much higher in number concentration than the concentration of large CCN in the monodispersed salt. Very few experiments have been successful in studying the efficiency of hygroscopic seeding agents, except the hygroscopic seeding experiments done in Texas convective clouds (Rosenfeld et al., 2010). The seeded cloud volume was identified unambiguously with sulfur hexafluoride (SF_6) gas tracer and the cloud physics aircraft was able to track very precisely the seeding aircraft location in real-time. Whenever trace concentrations of SF_6 were measured in cloud, it can be assumed that the cloud volume was impacted by the seeding. Seeding was done just below cloud base using monodispersed salt powder with 90% of the powder particles greater than 2 μm by mass. It was found that the seeded particles acted to create larger drops by extending the tail of the distribution. Such unambiguous confirmation of successful seeding by hygroscopic flares in convective clouds has not been found experimentally. Despite the lack of evidence, seeding with hygroscopic flares continues worldwide. There is a need for renewed interest in the advancement of manufacturing techniques to limit the number concentration of sub-micron particles in flares as well as to improve measurement techniques of the unambiguous identification of a seeding effect in clouds.

In both glaciogenic and hygroscopic seeding, seeding material must be properly applied to be effective. This is often referred to as 'targeting'. For example, during airborne seeding operations a radar meteorologist vectors the pilot into and around storm systems to locate suitable storms. The meteorologist is limited by the most recent weather information and observations, and what is displayed on radar; observations and forecast data that are at least minutes to hours old, and radar echoes of storms that are a few minutes old by the time the meteorologist observes them. The pilot is limited by not having a complete picture of the complexity of the storm system developing around the aircraft. Minutes and hours old information can lead to less effective targeting. Therefore technology of high operational readiness, or available in near real-time, is required for precise targeting and timely seeding actions.

Targeting is best evaluated by dispersing tracer material that is mixed in with the seed aerosol (e.g., Warburton et al., 1996; Allwine et al., 2002). It is beneficial to develop improved particulate, aqueous and/or gas phase tracer technology that can be combined with hygroscopic and glaciogenic seeding material. Sulfur hexafluoride (SF_6), for example, has been effective in urban dispersion and transport studies (e.g., Allwine et al., 2002), and it has potential for studying mixing processes in clouds (e.g., Stith and Benner, 1987). This technique might also be used in winter orographic cloud seeding. For example, SF_6 releases at proposed generator sites could validate that the seeding agent is dispersing as simulated by the model. However, SF_6 is a powerful greenhouse gas with a global warming potential of 22,800 times as strong as CO_2 and a 3200-year atmospheric lifetime, the highest identified by the Intergovernmental Panel on Climate Change (IPCC, 2014). It will be useful to identify possible replacement gases if they are deemed suitable for atmospheric dispersion studies.

Examples of technologies and techniques that might be operational or near operational readiness level include: (i) polarimetric radar measurements of precipitation hydrometeors (e.g., Liu and Chandrasekar, 2000; Kucera et al., 2008; Thompson et al., 2014), (ii) decision support tools, e.g., Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN; Dixon and Weiner, 1993), and (iii) instrumented UAS.

Polarimetric radar retrieval algorithms are based on work done by Liu and Chandrasekar (2000). These algorithms are derived from bulk electromagnetic scattering properties of various cloud hydrometeor types, microphysical theory and validation with previous observational studies. Kucera et al. (2008) used polarimetric radar observations in an exploratory hygroscopic seeding experiment and analyzed liquid water content, rainfall rates and hydrometeor type in seeded and unseeded clouds. Based on the analysis of selected case studies it was concluded that polarimetric radar could distinguish the effects of hygroscopic seeding. Thompson et al. (2014) tested the polarimetric radar data and algorithm output from winter storms alongside surface observations and thermodynamic soundings. It was confirmed that the algorithm is able to realistically discern regions dominated by wet snow, aggregates, plates, dendrites, and other small ice crystals based solely on polarimetric data.

In weather modification operations that target convective clouds, radar data is often processed with the TITAN software package. The volume-scan radar data allows analysis of different variables such as storm identification, location, area, volume, mass of precipitation, vertically integrated liquid as well as rates of variation of these parameters. TITAN provides a tool for an appropriately trained meteorologist to quantify a seedable cloud appropriately. A “storm” is defined as a contiguous region exceeding thresholds for reflectivity and size (Dixon and Weiner, 1993). An optimization scheme is employed to match the storms at one time with those at the following time and a short-term forecast of both position and size is based on a weighted linear fit to the storm track history data. In recent years TITAN has morphed into a larger software package with the same name. The current TITAN package is an entire software system that does not only support storm tracking and forecasting, but also a variety of tasks like merging individual radars into a mosaic and removal of radar artifacts. The TITAN system is used operationally in several weather modification projects worldwide.

Perhaps the most promising technology in atmospheric sensing over the last few decades is the use of unmanned aircraft systems (UAS) or unmanned aerial vehicles (UAVs). UAS have the potential to become a major resource for scientific research and weather modification. The capabilities of UAS have increased dramatically over the past decade, especially with improvements in autonomous flight performance. The ability to send a UAS on a mission without the need for a pilot greatly expands the potential for extended measurements while simultaneously lowering the operational costs. Over the last few decades government agencies and private sector companies have employed UAS for surveying and atmospheric research, including hurricane research and volcanic plume sampling. The feasibility of integrating UAS in weather modification operations or research has not been addressed and such a discussion is most appropriate.

2.2. Prospective technology for weather modification activities

The results of our identification steps have yielded prospective technology and/or techniques for cloud seeding. They are generally UAS, statistical methods, and high resolution modeling and simulation systems. Table 1 compares the technologies and techniques useful for weather modification purposes. Although UAS are deployed operationally worldwide, they have yet to be integrated in weather modification operations or research. A framework should be established before their integration.

High resolution modeling that simulates cloud processes and their response to cloud seeding activities (e.g., Xue et al., 2013, 2014), and statistical techniques developed during the Wyoming winter orographic seeding program (Breed et al., 2014) are close to operational readiness. Since their performance will still be significantly improved using comprehensive data gathered from operational activities, they are not considered operationally ready at the present time. Despite the significant improvement in the ability of numerical models to simulate cloud processes and the effects of seeding, resolving the need for more realistic outputs relies on an ability to overcome the challenges of validating their outputs (e.g., DeFelice et al., 2014). Computational architectural advancements are also expected, and might affect the operational readiness of the models used in cloud seeding activities within the next decade.

3. History of UAS for use in meteorological applications

UAS have been used since before the first manufactured UAV in 1916 (Fig. 2). Their use for meteorological and other environmental monitoring began in the 1990s, and became routinely used in the 2000s. National Oceanic and Atmospheric Administration (NOAA) missions, for example, have regularly used UAS since 2006 (e.g., Hood, 2014). The Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Unmanned Aerospace Vehicle (UAV) program was established in 1991 with UAS field campaigns conducted from 1993 to 2006. During this time period twelve UAS campaigns were conducted where airborne measurements were collected. Three different UAS platforms were used in these campaigns, namely the Gnat-750, the Altus and the Altus II (Stephens et al., 2000). The DOE ARM UAV program clearly demonstrated that measurements from UAS contribute to our understanding of cloud and radiative processes. Since the National Aeronautics and Space Administration (NASA) Global Hawk Pacific Mission (GloPac) demonstration of the Global Hawk's capability to be operated routinely to obtain science-quality data over remote atmospheric regions (Newman and Fahey, 2010), NASA and NOAA have conducted several other Global Hawk science missions. More recently, NASA has flown the Global Hawk during the Airborne Tropical Tropopause Experiment (ATTREX) mission to study the physical processes occurring in the tropical tropopause layer and determine the composition of air entering the stratosphere (Jensen et al., 2015). UAS technology have been shown to be capable of handling the challenges of validating data products from systems designed to model and simulate cloud processes (dynamics and microphysics) under a wide range of natural environments. Unmanned systems might also help improve seeding operations and quantify their efficiency.

4. Unmanned vehicles or systems for cloud seeding operations and monitoring

In the context of this paper, an unmanned airborne vehicle (UAV), unmanned aircraft system (UAS), or an unmanned ground vehicle (UGV) is considered an observing system. An observing system generally consists of:

i. multiple sensor platforms (e.g. ground, satellite, aircraft, UAS, UGV),
ii. multiple sensors with, or without, non-uniform spatial, spectral characteristics at multiple atmospheric levels,
iii. application-specific observing/monitoring capabilities (e.g., hydrologic cycle precipitation amount, hydrometeor microstructure, soil moisture, latent heat flux, turbulence),
iv. a processing system for these data, and
v. a dissemination capability to provide (and archive) data as needed.

An unmanned system used for cloud seeding operations would require two basic components, namely to (a) identify atmospheric conditions conducive to seeding (e.g., precipitation augmentation, hail

Table 1
Comparison of technologies for weather modification operations.

Technological advancement	Risks/issues (wrt operational use)	Benefits	TRL[a] or SRL[a]
Polarimetric radar measurements	Expensive; resolution	Good temporal and spatial coverage; measurement of concentrations of cloud hydrometeors; hydrometeor phase differentiation	Operational
TITAN	Computational and algorithm limitations.	Minimizes analysis bias; established community user support	Operational
Instrumented UAS research platforms	FAA[a] restrictions; miniaturization of sensors	Comprehensive data cubes that provide a more representative understanding of system to be seeded and effect seeding had, plus yield better models and improve seeding protocols.	Near operational
High resolution modeling that simulates cloud processes and their response to cloud seeding activities (e.g., Xue et al., 2013, 2014)	Need more explicit aerosol-nucleation, microphysical, hydrology, and hydro-meteorological routines and their interfaces. Data to develop the latter are sparse and costly. Must account for (or code) at data natural space and time frequency to reduce computational noise from their combined routines, maximize output accuracy and latency. Inaccurate representation of particle dispersion may lead to misleading results. Need for periodic validation with observations.	Such models will become the standard for simulating the system, and the effect of seeding; evaluating the effectiveness of the seeding event, and planning efficient seeding operations. Excellent tool for feasibility studies.	Prototype to near operational
New statistical techniques (e.g., Breed et al., 2014)	Experimental. Large sample size is needed to reach statistical significance.	Evolution of a standard statistical technique to better handle seeding activity evaluations.	Prototype
UAS for cloud seeding operations	FAA[a] restrictions; high cost to develop seeding agent delivery systems	More accurate, automated and controlled operations should lead to more precise targeting.	Pre-prototype
Geoengineering technologies and techniques (Cotton, 2009)	Poorly formulated concepts on engineering, science, and technology principles.	None at present. Very high cost to develop and overcome scientific/technological issues.	Not even at the concept level

[a] FAA — Federal Aviation Administration; TRL — technology readiness level; and SRL — software readiness level.

suppression, and (supercooled) fog dispersal) and (b) implement the seeding.

The process for developing an unmanned system for either basic role could generally proceed by engaging standard project management principles, processes, and tools as follows:

i. Identify, design, develop, test and document the sensing suite that will optimally provide temporal, spatial (and spectral) sensitivities to overcome the predictability or sparseness of environmental parameters.
ii. Design, develop, test and document the information processing system for producing and disseminating the information obtained by the sensing suite from (i).
iii. Design, develop, test and document the Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR; e.g., C4ISR Architecture Working Group, 1997) for this system.
iv. Design, develop, test and document the optimal integration scheme of the payload sensor suite, processing system, protection, and C4ISR components on the sensor suite identified under (i).
v. Integrate (ii) through (iv) and test operability.
vi. Perform optimization trade studies as needed.
vii. Field test, develop, deploy, and maintain system.

The sensor and sensor coverage component will depend on the requirements of the systems. The requirements will depend on the application. Some relevant measurement categories for cloud seeding operations could include; aerosol, microphysical, gas phase, thermodynamic, hydrologic, auxiliary and ancillary. The measurements will need to encompass the aerial footprint on the surface as well as the spatial resolution of the measurements, and the temporal repeat frequency. A sensor will have to provide information about absolute, or process parameters at twice their natural temporal and spatial variability to ensure a representative natural data parameter field.

Data processing architecture should be able to handle real-time, near terabyte per second data volumes, and data of multiple formats. It should also be able to accept and send secure communications. It will also require an on-board archive and ground station archive points to facilitate operational activities, ensure protection and minimize data

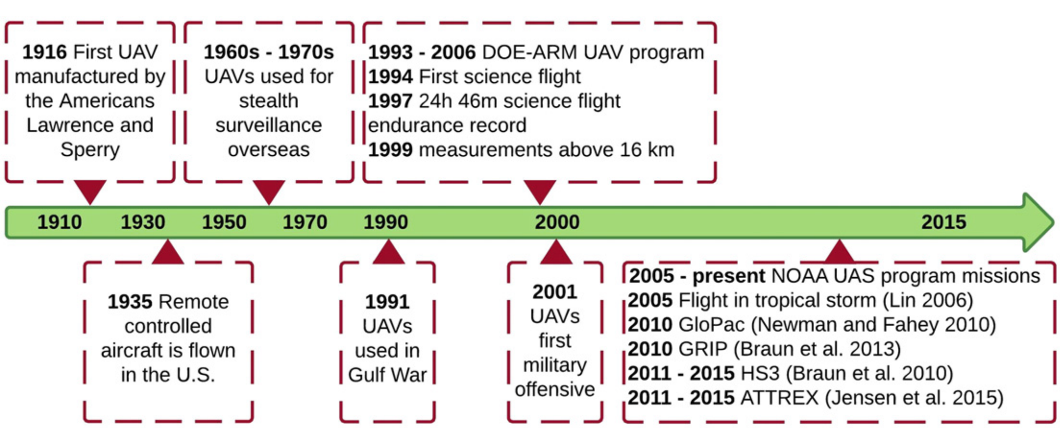

Fig. 2. A history of UAS usage [Based on Stephens et al. (2000); NOVA (2002); Fahey et al. (2006); Scheve (2008); Braun et al. (2010); Braun et al. (2013); Gupta et al. (2013); Hood (2014)].

loss. Thus a cloud seeding-related UAS needs an architecture designed to be as responsive when all (its) components are running simultaneously at full capacity as when only one component is operating at capacity. Each component must be configured to interact with each of the other components without affecting system throughput or the efficiency and accuracy of an individual computational algorithm.

The actual design and sensor configuration of the UAS will depend on its objective or role, such as identifying operational opportunities and even evaluating or monitoring them, or as conducting operations. We constructed Table 2 to provide high-level conceptualized unmanned systems for identifying cloud seeding opportunities and for carrying out cloud seeding operational activities. An actual system might contain a subset of the capabilities shown in Table 2.

Table 3 provides a sampling of relevant payloads that are nearly operational or operational, based on their readiness for use on an unmanned platform (i.e., Technology Readiness Level, TRL), and that could be used to support cloud seeding operations and their evaluation. Some experimental UAS sensors worth tracking include:

i. Micro-cloud particle imager (Micro-CPI; based on Lawson et al., 2001) to measure the size distributions of water and ice particles ranging from 1 μm to several millimeters;
ii. The backscatter cloud probe with polarization detection (BCPD; based on Beswick et al., 2014) to measure water and ice particle size distributions in the 2–50 μm range and discriminate between water and ice particles;
iii. Printed optical particle spectrometer (POPS; Gao et al., 2015) for measurements of aerosol number concentrations and size distributions;
iv. Aerosol counting, composition, extinction and sizing system (ACCESS; Bates et al., 2013) for rapid observations of ambient total particle number concentration, aerosol size distribution, aerosol composition and aerosol absorption;
v. Miniature scanning sun photometer (Murphy et al., 2016) for vertical profiles of solar irradiance and sky radiance in four wavelengths; and
vi. Sensors for chemical composition determinations to support air quality and aerosol studies, for example:
   - Uninhabited aerial vehicle atmospheric water sensor package (UAVAWSP) for in-situ N_2O, H_2O isotopes, HO, CO, and CH_4 measurements (Khan et al., 2012).
   - Advanced whole air sampler (AWAS; Fabian, 1981) for CFC, Halon-1211 for NMHCs, CO, CH_4, and N_2O measurements.
   - UAS chromatograph for atmospheric trace species (UCATS) for N_2O, SF_6, CH_4, CO, and O_3 measurements.
   - Unmanned aerial mass spectrometer system (UAS-MS) for in-situ volcanic plume sampling of gas volatiles (Diaz et al., 2015).
   - Open-path cavity ring-down spectroscopy (CRDS) sensor for sampling of ammonia and methane onboard UAS (Shadman et al., 2015).

Table 2
Conceptual system to identify and monitor cloud seeding opportunities [to conduct cloud seeding operations].

Function	Capability
Sensing	Atmospheric profiles surface to flight-level: air temperature, dewpoint temperature, 3D wind components (u, v, w), turbulent fluxes (u′, v′, w′), static pressure, spectral irradiance, supercooled liquid water content (SLW) Atmospheric constituents and composition (aerosols, cloud, precipitation, trace gases, total water content) Surface characteristics (spectral reflectance, soil moisture, soil temperature profiles) Ancillary, auxiliary (e.g., GPS, GTOPO30 and GTOPO05, platform velocity, acceleration and attitude, video) [AgI, dry ice (DI), hygroscopic agent dispenser]
Sensor coverage	Omni-slight skew toward forward hemisphere; [Sub-UAV point[a] (AgI)]
Data processing	Able to process 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; Ahern et al., 2008); Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR); 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, C4ISR, sensing); data logging; data processing]
C4ISR[b]	Secure, remote, virtual platform

[a] Sub-UAV Point is defined as the "point of intersection with the earth's surface of a plumb line from the UAV to the center of the Earth" (i.e., intersects surface at a 90 degree angle).
[b] C4ISR- Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance. This component must at least be able to consolidate several high bandwidth ingests and be network capable, distinguish single-data-link disparate data and route securely to the appropriate end user, as well as provide functionality and appropriate bandwidth, compression, imagery frames per second and resolutions in accordance with user capabilities.

For example, Goddard Space Flight Center (GSFC) used a high-altitude imaging wind and rain airborne profiler (HIWRAP) and ER-2 X-band Radar (*EXRAD*) radar system onboard a Global Hawk UAS to study the vertical structure of precipitation and air motions in a mesoscale precipitation system (Li et al., 2016). These instruments operate at different frequencies and collectively provide a more complete reproduction of the actual range of precipitation-sized hydrometeors and their location inside the cloud. The latter provides insight into the dynamics of that cloud system and its colloidal stability, for example. The microstructure and colloidal stability are important considerations for cloud seeding operations (e.g., DeFelice and Czys, 2016).

Given our focus on the practicality of the UAS platform and the design of its payload for weather modification activities, if one of the sensors and payloads in Table 3 are used, sensor payload weight and location on the platform will need to be aerodynamically optimized. Before the location of the sensors can be optimized, the platform that can handle the chosen sensors has to be identified. Besides the weight, additional concerns lie with regard to the aerodynamic effect of the payload and the endurance required for cloud seeding operations. Table 4 summarizes a comparison among a representative set of UAS platforms of various sizes and takeoff weight. Although small UAS like the Manta can only carry 6.8 kg of payload compared to the 860 kg of the Global Hawk, the Manta has flown science missions in the Maldives during the Maldives Autonomous UAV Campaign (MAC; Ramana et al., 2007) and in Norway during the Cooperative Investigation of Climate-Cryosphere Interactions campaign (CICCI; Bates et al., 2013). The Aerosonde UAV with a payload of 4.5 kg has been widely utilized as a platform for measurements of the local circulation, the thunderstorm environment, sea surface temperature as well as wind direction and speed in a typhoon eyewall (Lin, 2006). Rapid deployment UAS with a 1 kg payload such as the Coyote have been deployed to study the air–sea interface (Patterson et al., 2014). Therefore, small (lightweight) UAS have also shown to be applicable for atmospheric research.

In weather modification operations, small UAS might be capable of carrying some seeding material in the form of ejectable or burn-in-place flares, each weighing 20 g. A larger UAS would likely need to carry AgI acetone solution and/or salt micro-powder. For example, at least ~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, a small UAS with a maximum takeoff weight of 25 kg (and a payload of 6–10 kg) would not be able to carry any salt seeding material. Another potential issue relates to the inevitable need for a C4ISR component to the payload (i.e., its 'brains'). This unit will be used in part to support targeting of the seeding agent that ensures the material reaches the right place, at the right time. The cloud water inertial probe (CWIP;

Table 3
Sensors and payloads for UAS equipped to identify clouds suitable for seeding, conduct seeding operations and collect data for scientific research.

Title	Acronym	Type	Measurements	TRL[a]
Advanced Vertical Atmospheric Profiling System[b]	AVAPS	Dropsonde (mini-RD-93)	Pressure, temperature, humidity, wind field profile	Operational
Lightning instrument package[b] (Blakeslee et al., 2014)	LIP	Electric field mills	Electric field vector components	Operational
Cloud Physics Lidar[b] (McGill et al., 2002)	CPL	Active, lidar	Aerosol, optical depth, size distribution; cirrus, sub-visual cirrus	Operational
High Altitude Monolithic Microwave integrated Circuit (MMIC) Sounding Radiometer[b] (Brown et al., 2011)	HAMSR	Microwave radiometer, sounder	Temperature, H2Ov, precipitation profiles	Operational
High Altitude Imaging Wind and Rain Airborne Profiler[b] (Li et al., 2008)	HIWRAP	Radar, scatterometer	Radar reflectivity, doppler velocity, winds	Operational
Nuclei-Mode Aerosol Size Spectrometer[b] (Axisa et al., 2013)	NMASS	CN counter, spectrometer	Condensation nuclei, aerosol size distribution	Operational
Hawkeye[b] (based on Lawson et al., 2001)		Camera, forward scatter, optical array	Hydrometeor size and image	Operational
Cloud Droplet Probe (Lance, 2012)	CDP	Spectrometer	Cloud drop size distribution	Operational
Back-scatter Cloud Probe (Beswick et al., 2014)	BCP	Spectrometer	Aerosol/cloud particle size distribution	Operational
Cloud Water Inertial Probe	CWIP	Hotwire, advanced heading reference system, 5-hole gust probe	Liquid water content, temperature, relative humidity, pressure, 3D wind components (u, v, w)	Operational
Solar spectral flux radiometer[b] (Pilewskie et al., 2003)	SSFR	Pyranometer	Solar spectral irradiance	Operational
Airborne compact atmospheric mapper[b] (Kowalewski and Janz, 2009)	ACAM	Visible imagery, spectroscopy	NO_2, O_3, aerosol, SO_2, CH_2O	Near operational
Cloudsonde-radiosonde SLW detector (Hill, 1989, 1990; Hill and Woffinden, 1980)	RSLWD	Balloon & drop-sonde capable	Pressure, temperature, SLW content, wind field profile	Prototype
Ice detector (Otto et al., 2006)		Vibrating rod	Rate of ice accretion	Operational
Seed payloads — generators with AgI solution (Hill, 1985 personal communication), and racks with burn-in-place and/or ejectable flares		Acetone-AgI canister, flares		Pre-prototype

[a] TRL — technology readiness level; but must use an appropriate platform.
[b] Previously deployed on NASA Global Hawk.

Table 3), the back-scatter cloud probe (BCP; Table 3), a first person view (FPV) camera (with video transmitter) and other sensors can be used to provide additional information relevant to support targeting, for example. A minimum payload for targeting support consisting of the CWIP, BCP and FPV camera is estimated to weigh 2.8 kg and system firmware could be programed to perform seeding autonomously. A more sophisticated payload would deploy the Micro-CPI and BCPD to measure the relative concentrations of water and ice particles in clouds. This additional capability allows for the detection of abnormally high concentrations of small ice crystals.

Table 4
Characteristics of some UAS for general comparison.

UAS	Max. altitude (km)	Endur-ance (hours)	Max. takeoff weight (kg)	Useful speed (m/s)	Useful payload (kg)
Ikhana[a]	12	24	4535	85	907
Global Hawk[b]	18	30	11,600	160	861
Viking 400[c]	4.5	11	235	30	45
Sierra[d]	3.6	10	181	30	45
Shadow MK-1[e]	4.5	6	90	55	25
BAT 4[f]	3	8	45	35	13
Manta[g]	4.8	6	27	25	6.8
UAV Factory Penguin B[h]	3	8	21	25	6
Latitude HQ-60[i]	4.2	15	43	20	5.4
Textron Systems Aerosonde[j]	4.5	10	25	31	4.5
Scan Eagle[k]	6	20	20	25	2.8
Coyote[l]	6	1.5	5.9	30	0.9

[a] https://airbornescience.nasa.gov/aircraft/Ikhana
[b] https://airbornescience.nasa.gov/aircraft/Global_Hawk; Hood (2014)
[c] https://airbornescience.nasa.gov/aircraft/Viking-400
[d] https://airbornescience.nasa.gov/aircraft/sierra
[e] http://www.icarus.upc.edu/en/facilities/experimental-facilities; Hood (2014)
[f] https://airbornescience.nasa.gov/aircraft/BAT_4
[g] http://www.pmel.noaa.gov/edd/pmel-theme/manta
[h] http://www.uavfactory.com
[i] http://latitudeengineering.com/products/hq/
[j] http://www.textronsystems.com/products/unmanned/aerosonde
[k] https://airbornescience.nasa.gov/aircraft/Scan_Eagle
[l] http://www.raytheon.com/capabilities/products/coyote/

UAS for cloud seeding operations should, like other airborne cloud seeding platforms, be equipped to handle the most severe turbulence and icing conditions. The CWIP can measure temperature, turbulent fluxes and liquid water content that could provide information on the turbulence intensity that is being encountered by the aircraft. UAS are more likely to survive turbulence than icing. Recent studies have focused on the application of super-hydrophobic coatings on aircraft surfaces as an ice-mitigation tool. These surfaces have a high degree of water-repellency at low-speed but there is little research with UAS in a flight environment. Detailed experiments have been conducted in icing wind tunnels to measure the ice adhesion strength of various super-hydrophobic coatings by subjecting the surfaces to a supercooled icing cloud (Swarctz et al., 2010; Yeong et al., 2015). When compared to an untreated sample, super-hydrophobic surfaces inhibited initial ice formation. After a period of time, random droplet strikes attached to the super-hydrophobic surfaces and started to coalesce with previously deposited ice droplets, accreting ice across the surface. It was also found that increased droplet impact speeds tend to increase the ice adhesion strength on the coatings (Yeong et al., 2015). Therefore it is apparent that super-hydrophobic coatings may not be suitable for repetitive or prolonged supercooled cloud penetration unless heating devices are used on aircraft control surfaces. To protect the UAS from heavy ice accretion, an ice detector can be used to determine the amount of airframe icing and perform autonomous de-icing maneuvers based on temperature data collected during the ascent.

In view of all payload limitations, small UAS have operated successfully in the vicinity of thunderstorms as part of an observational campaign. The UASUSA 'Tempest' was operated as an observational platform during the Verification of the Origins of Rotation in Tornadoes Experiment, or VORTEX2, field campaign. The Tempest measured meteorological state parameters and wind along gust fronts associated with supercell thunderstorms (Elston et al., 2011). Therefore it is technologically possible for small UAS to conduct weather modification research and operations but several issues and risks need to be investigated via trade studies, for example, before this is possible.

5. Issues and risks

The risks, issues and concerns surrounding the use of UAS platforms for weather modification activities may be categorized into four categories: (a) Federal Aviation Administration (FAA) and equivalent regulatory agencies, (b) functional (which primarily entails measurements, data integrity, quality and dissemination and storage, as well as the platform performance), (c) programmatic, and (d) other. The remainder of this section highlights the primary risk, issues and concerns related to each category.

a) Federal Aviation Administration (FAA) and equivalent regulatory agencies.

The FAA is responsible for air safety from the ground up. Consistent with its authority, the FAA presently has regulations that apply to the operation of all aircraft, whether manned or unmanned, and irrespective of the altitude at which the aircraft is operating. The FAA regulations also prohibit routine operation of UAS over densely populated areas and any person from operating an aircraft in a careless or reckless manner so as to endanger the life or property of another.

The use of UAS for weather modification operations is likely to fall under civil and possibly public categorizations. The FAA regulations currently require civil UAS to operate a certified aircraft and a (UAS) certified pilot to access the National Air Space (NAS) (FAA, 2016). Public UAS require a certificate of waiver or authorization (COA) to fly in civil airspace. The COA will allow an operator to use a defined block of airspace and includes special provisions unique to the proposed operation, such as, requiring flight under visual flight rules (VFR) only, and/or only during daylight hours. COAs usually are issued for a specific period, generally up to two years in many cases. Most COAs require coordination with an appropriate air traffic control facility and may require a transponder on the UAS to operate in certain types of airspace. Since UAS technology cannot currently comply with “see and avoid” rules that apply to all aircraft for collision avoidance, a visual observer or an accompanying “chase plane” must maintain visual contact with the UAS and serve as its “eyes” when operating outside airspace restricted from other users. Collision avoidance includes the avoidance of other traffic, clouds, obstructions and terrain. An example of UAS operations with a COA is the VORTEX2 field campaign where the Tempest was flown in a thunderstorm environment with observers maintaining visual sight of the UAS at all times.

A state law or regulation that prohibits or limits the operation of an aircraft, sets standards for airworthiness, or establishes pilot requirements generally would be preempted by a FAA issued COA. But state and local governments do retain authority to limit the aeronautical activities of their own departments and institutions. Under most circumstances, it would be within state or local government power to restrict the use of certain aircraft, including a UAS, by the state or local police or by a state department or university.

There are equivalent FAA organizations across the globe that have regulations for using UAS. Table 5 provides coarse highlights of the regulations for some countries that have had weather modification activities.

There are technical barriers related to the safety and operational challenges associated with enabling routine UAS access to the NAS (e.g., Dalamagkidis et al., 2008). For example, the assurance of safe separation distances between unmanned aircraft and manned aircraft when flying in the national airspace; flight in severe weather; safety-critical command and control systems and radio frequencies to enable safe operation of UAS; human factors issues for ground control stations; airworthiness certification standards for UAS avionics and integrated tests and evaluation designed to determine the viability of emerging UAS technology (NASA, 2014). This is especially the case for weather modification operations where UAS flight would need to be conducted inside or near clouds in an airspace that is accessible to all aircraft. Not being able to fly within clouds, or in severe weather, or in-cloud close to mountains where civilian aircraft are not allowed to fly for example, would present a serious limitation. While out of cloud environmental measurements are of great benefit to study the thermodynamic environment in which these clouds form, UAS operators will have to devise means to work around such limitations and build upon procedures established by NOAA and NASA UAS missions that study hurricanes and other severe weather. It might be possible, for example, to conduct cloud seeding below cloud base without entering the cloud or to drop flares in cloud tops without penetrating cloud. These types of procedures would need to be approved by the aviation regulatory agency (e.g., FAA COA).

Table 5
UAS usage for some countries across the globe.
(Derived from CASA, 2013; Transport Canada, 2013).

Other countries with UAS operational regulations	Commercial use	Notes
Australia	✓	An “Unmanned Aircraft System” profit-seeking “air work,” has requirements including pilot certification.
African nations		Relatively unregulated, especially for agriculture and other purposes.
Canada	✓	Require Special Flight Operations Certificates.
Mainland Europe	✓	Most of mainland European countries operate under jurisdiction of European Aviation Safety Agency (EASA), and need certification in any situation. Certification is granted on a case-by-case basis.

b) Functional

Functional issues with UAS cloud seeding platforms involve the representativeness, quality, and use of the data they use and collect. They generally, but not exclusively, encompass issues and risks from data to information conversion, dissemination and its interpretation, such as; scaling (of various sensor-derived data), primary standard devices for measurements, graceful degradation, algorithm computational architecture and decision support tools. From a measurement perspective, the goal is to maximize data quality and representativeness (e.g., DeFelice, 1998) from the sensors on the UAS platform. This will mean conducting a set of trade studies during the design phase to maximize data quality and representativeness despite, for example, issues related to the computational architecture, graceful degradation and/or operational availability of the highest possible quality data.

Computational architecture issues might entail algorithm input/output, data integrity and quality, data information dissemination and storage, for example. The collection of data, or the data cube from this system will contain variables that have differing natural variations in space and time in the atmosphere–hydrosphere–earth system. They may also have modal differences (e.g. visible, microwave, IR, electro-optical). The differing natural variations in space and time, and mode, are certainly important when assuring data quality, but are arguably more important when being fused into useful operational information. A conceptual depiction of this issue with regard to spatial resolution is shown in Fig. 3.

Graceful degradation (of sensors) and the operational availability of parameters required during operations refer to the very possible scenario when a sensor fails, and/or no data and/or poor quality data will be available to support the operational need. The result could be costly, since the information derived could be significantly different from reality causing less than optimal operational or post operation evaluation results.

c) Programmatic

The main programmatic operational concerns are the equipment required to conduct the project, the size of the team required to

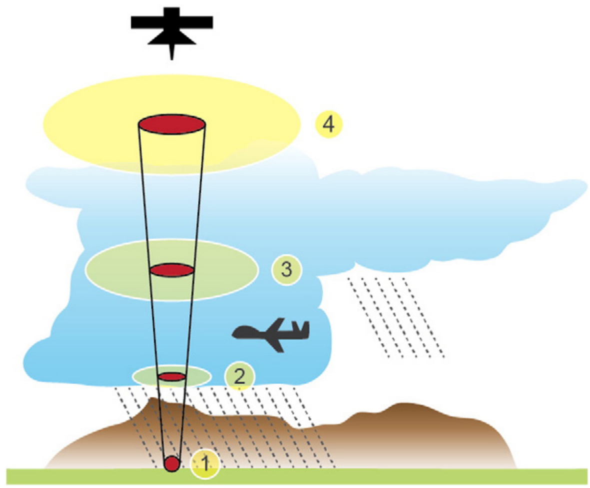

Fig. 3. Conceptual relationship of pixel-level information as a function of platform. Shaded area represents the relative spatial extent of typical sensors on the noted platforms. In this Figure, (1) represents the relative extent of ground based sensor measurements; (2) represents the relative extent of UAV based sensors with moderate resolution measurements and/or satellite based sensors with high resolution measurements; (3) represents the relative extent of UAV based sensor with low to moderate resolution measurements and/or satellite based sensors with moderate resolution measurements; and (4) represents the relative extent of satellite based sensors with low resolution measurements.

implement such an operation and the inherent logistics. The crew size may be significantly greater for small projects, and perhaps similar and slightly smaller for larger projects. Larger projects will require more UAS' hence there will need to be a trade study to determine the optimal team size as a function of the number of UAS' used, and to consider how many UAS' would practically be handled by a crew of a certain size.

d) Other

There may be concerns or risks of interference with UAS' communications, security, and/or data interpretation derived from the resident components on such platforms. The latter risks are identical to virtually all observational platforms with like sensing and communication requirements. There are ready resources of information available on ensuring communications are secure.

6. Benefits

Despite the risks and issues there are some benefits. The most significant benefits may include:

1. Ability to conduct weather modification operations in remote or mountainous areas for a long duration without concern of personnel loss.
2. Improved evaluation of seeding activity data. That is, enhance the probability of operational accuracy and success. This is possible by acquiring more routine observations of the cloud environment.
   i. UAS have the capability to obtain a comprehensive data cube of relevant seeded cloud system measured parameters made at various altitudes above the ground, and the corresponding remote sensing measurements made at various spatial resolutions. In addition to needing aircraft in-situ and remote sensing measurements to evaluate ground-based and spaceborne remote sensing retrievals, UAS measurements at resolutions higher than those possible with satellites, offer a critical missing link for determining how aerosol and cloud properties vary over scales at finer than satellite scales. These observations are also needed more routinely in operational weather modification programs.
   ii. Observations over the complete cloud life cycle are lacking. Manned aircraft equipped with in-situ and remote sensors can track the life cycle of cloud systems over a relatively short period of time. Due to the limited endurance of manned aircraft, it is difficult to obtain measurements of clouds at all stages of development. With the development of long-duration (>8 h) UAS platforms, it may be possible to observe clouds over multiple lifecycles so that data can be analyzed with statistical rigor.
   iii. Data collection and case selection for randomized seeding studies can be enhanced using UAS. UAS equipped with algorithm driven seeding actions are suited for long-term randomized cloud seeding experiments over unpopulated and remote regions. Long time series properties of seeded and non-seeded clouds have allowed scientists to study the effect of cloud seeding. In most instances, the number of cases falls below the number that is required to achieve statistical significance. With the long-term deployment of instrumented UAS at a number of locations, databases of cloud properties may help achieve a level of statistical significance that may not be possible otherwise. For example, the CWIP's cloud seeding score algorithm is a measurement-based system that compares measured data to thresholds. If thresholds fall within range, the seeding score is high and seeding is recommended.
   iv. Improved representative model parameterizations, or data fields with optimal spacing will improve processing throughput while maximizing quality by acting as input into coupled models. The latter would also facilitate the development, improvement and/or validation of weather modification-relevant operational and evaluation models, and decision support tools. Often model performance is not evaluated adequately due to lack of suitable observations. Model errors are uncharacterized leading to incorrect model guidance and seeding actions. Little data are available for assessing sub-grid processes that describe thermodynamic surface variables. Descriptions of these variables are needed to determine the planetary boundary layer initiation schemes. Routine UAS profiles of thermodynamic parameters, as well as wind data at high data rates, would give the statistics needed to address sub-grid variability.
   v. Evaluation of numerical models using data that captures natural atmospheric variability is required. In typical field experiments a small number of representative case studies are sampled and studied to describe a typical cloud system. Often these cases are associated with substantial variability and it is difficult to characterize typical behavior. Numerical models are often used to explain atmospheric variability and atypical behavior of cloud systems. UAS observing platforms facilitate routine data collection that captures the time evolution that can be compared to numerical models.
3. Substantive advancements in the science and its application for the disciplines that involve the cloud life cycle in any capacity (e.g., data on concurrent Eulerian and Lagrangian perspectives over sub-cloud scales; hydrologic cycle efficiency, climate change quantification and predictions), as well as in the support of solutions to relevant socio-economic issues (i.e., drought, more destructive hurricanes).

7. Summary

In this review we take a first look at the use of unmanned aircraft systems (UAS) for weather modification applications and present the benefits and challenges faced by the technology regarding UAS. We see promise for the future use of UAS, and identify the more significant anticipated initial issues related to their use. The issues are primarily related to government policy, technology advancements, and operational considerations. Technological advancements, the risks, issues and concerns for adapting them for cloud seeding operations and the benefits from their use are summarized (Table 1). Despite all that was highlighted in this review, overcoming the risks will help ensure that UAS configured for weather modification operational use may be ready in time to handle the impending increased volume of weather modification-relevant demands arising from growing socio-economic issues, most notably minimizing the negative effects of anthropogenic contributing factors (population increase) and natural contributing factors to impending water shortage over our earth. Documenting cloud characteristics to confirm the initial cloud state that is consistent with weather modification theory, or, to improve the application of numerical models must be a priority.

Immediate demand exists for small UAS with simple, calibrated and well validated payloads that measure meteorological state parameters, wind, turbulence, cloud hydrometer size distributions and liquid water content in conditions that are conducive to seeding. In its simplest form, the UAS for cloud seeding should include sensors designed to provide 'real-time' in situ-based measurements of turbulence and icing to support real-time operational flight guidance of the UAS, to navigate autonomously to areas of suitable temperature, increased updraft and regions of high liquid water content for best targeting. This simple application will improve and validate model parameterizations especially when applied to simulating seeding agent dispersion. Further, UAS configured for validation and monitoring of operational weather modification activities, which fly in tandem with UAS for weather modification operations, will allow for near-realtime Eulerian and Lagrangian analyses of transport and dispersion of seeding materials, for example. Perhaps the most sophisticated UAS deployment would be in long-term randomized cloud seeding experiments. UAS technology and their automation through algorithms would best benefit randomized cloud seeding experiments, which have become less frequent in the last decade. Ultimately, perhaps such UAS systems may allow for concurrent, near-real-time Eulerian and Lagrangian analyses of the processes of seeded cloud systems throughout their life cycles on sub-cloud scales. Unmanned aircraft system operations cannot and will not replace manned aircraft operations, although some manned aircraft missions could someday be accomplished by UAS. In this review we provided context and initial guidance for operators that might integrate UAS technology in future weather modification operations.

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