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Evaluation of Routine Atmospheric Sounding Measurements using Unmanned Systems (ERASMUS) Science Plan

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Summary

The use of unmanned aerial systems (UAS) is becoming increasingly popular for a variety of applications. One way in which these systems can provide revolutionary scientific information is through routine measurement of atmospheric conditions, particularly properties related to clouds, aerosols, and radiation. Improved understanding of these topics at high latitudes, in particular, has become very relevant because of observed decreases in ice and snow in polar regions.

Here, we propose to operate a variety of instrumented UASs during two, 2-week campaign periods in 2015 and 2016 at the U.S. Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility's Oliktok Point deployment. This campaign, named Evaluation of Routine Atmospheric Sounding Measurements using Unmanned Systems (ERASMUS), will serve two main purposes. First, it will support the collection of a detailed set of atmospheric measurements designed to complement those concurrently obtained by the third ARM Mobile Facility. This set of measurements will provide researchers with a focused case study period for future observational and modeling studies pertaining to arctic atmospheric processes. Measurements will be geared toward improved understanding of arctic moisture, aerosol, and radiation budgets. In particular, we aim to supply data for addressing the following scientific questions:

- How do profiles of temperature and humidity evolve during transitions between clear and cloudy atmospheric states?
- How do aerosol properties vary with height at high latitude locations?
- How well do current remote sensing retrievals perform in the arctic environment?
- What is the spatial variability of heat and moisture fluxes over ice and land surfaces?

The second purpose served by the ERASMUS campaign is to evaluate the potential for future routine atmospheric measurements using UAS at Oliktok Point. The ability for DOE to activate restricted airspace around Oliktok Point makes it a valuable resource for UAS-based measurements, and ERASMUS will provide feedback on the current ability to complete routine atmospheric sounding using these platforms. Information on environmental constraints, site-induced operational limitations, and general operational strategies will be provided in the form of a final report. This information should be helpful in the planning and execution of future UAS-based measurement campaigns at Oliktok Point.

Acronyms

AMAP	Arctic Monitoring and Assessment Program
AMF3	third ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
BER	Office of Biological and Environmental Research
CCN	cloud condensation nucleation
CESD	Climate and Environmental Science Division
CGR-4	a type of pyrgeometer
DOE	U.S. Department of Energy
ERASMUS	Evaluation of Routine Atmospheric Sounding Measurements using Unmanned Systems
GCM	global climate model
PI	principal investigator
POPS	Printed Optical Particle Spectrometer
PTH module	dropsonde instrument package
SPN-1	broadband shortwave radiometer
UAS	unmanned aerial system

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1.0 Project Description

This field campaign will deploy two different unmanned aerial systems (UAS) to Oliktok Point, Alaska, to sample atmospheric thermodynamics, radiation, and aerosols. To accomplish this, two deployment phases will be executed. The first phase will feature 2 weeks of DataHawk UAS operations during the summer of 2015. The second will feature a 2-week deployment of the Pilatus UAS during the spring of 2016.

The types of UAS-based measurements proposed will facilitate improved understanding of the lower arctic atmosphere, including aerosols and clouds, by providing vital data for analysis and model studies. These studies will subsequently foster the advancement of predictive understanding of the Earth's climate and environmental systems through improvement of global climate models (GCMs), thereby aiding in addressing the U.S. Department of Energy (DOE) Office of Biological and Environmental Research (BER) Climate and Environmental Science Division (CESD) mission to improve climate data and models for policymakers.

2.0 Introduction and Motivation

The Arctic is experiencing accelerated changes in climate relative to other parts of the globe (e.g., Serreze and Francis 2006). Extended monitoring efforts such as those underway at the ARM Climate Research Facility's North Slope of Alaska Site have demonstrated the importance of atmospheric processes in the modulation of the surface radiation budget in high-latitude environments. These influences on surface radiation budget directly translate to surface and near-surface temperatures, making understanding of radiatively relevant atmospheric components such as clouds and aerosols a necessary first step in improving our understanding of the evolution of surface properties such as sea ice thickness and extent and permafrost depth (e.g., Kay and Gettelman 2009; Romanovsky et al. 2011). While understanding the atmosphere is vital to accurate simulation of arctic climate, many questions about physical processes important to understanding the Arctic's atmosphere remain.

Research from the past decade has resulted in steady advancement in our overall knowledge and understanding of arctic cloud systems. Of the different types of arctic clouds, numerical models of all scales have been demonstrated to particularly struggle with the simulation of super-cooled, liquid-containing clouds (e.g., Klein et al. 2009; de Boer et al. 2012). Because of the strong influence of this liquid on atmospheric radiation, these clouds in particular are a major contributor to model biases in surface temperature at high latitudes (Shupe and Intrieri 2004). Many of the open questions surrounding these clouds result from incomplete information on the budgets that govern their existence. Budgets of atmospheric moisture, aerosols, and radiation all play critical roles in the formation, lifetime, and eventual dissipation of mixed-phase clouds (Morrison et al. 2012).

Our insufficient understanding of budgets governing mixed-phase cloud life cycles is partly the result of the limitations imposed by the capabilities of our current observing systems. When it comes to routine measurements, the arctic observing network generally revolves around the following three principal technologies:

- surface-based in situ measurements of key meteorological (e.g., temperature, humidity, wind, etc.) and aerosol (e.g., concentration, chemical composition, size, etc.) properties

- balloon-based profiling of key meteorological properties
- surface- and space-based remote sensing of cloud and aerosol properties using radars, lidars, radiometers, and other instrumentation.

These routine observations are occasionally complemented by intensive field campaigns that may introduce additional vertical profiling through the use of aircraft-based in situ instrumentation or more frequent radiosonde launches. While this observing network generates a large amount of information to process, there is a growing belief in the arctic science community that significant advances in understanding of processes within the often stratified arctic atmosphere require *frequent and routine profiling of atmospheric dynamical and thermodynamical properties, as well as cloud and aerosol properties*. Several recent studies have discussed the role of stratification in the lower arctic atmosphere and its role in governing cloud and aerosol properties (e.g., Persson et al. 2002; Sedlar et al. 2012), and because of the presence of this stratification, surface-based measurements often are not sufficient to improve process-level understanding. While remote sensors do provide a glimpse into processes occurring at altitude, some of the retrievals used to derive cloud properties (e.g., cloud droplet size, liquid and ice water path, etc.) are not necessarily well characterized, resulting in significant uncertainty and an inability to constrain budgets to the levels necessary to improve our overall grasp on atmospheric processes. In addition, the limited frequency of radiosonde profiling of temperature, moisture, and wind sometimes makes it challenging to interpret data from surface-based remote sensors.

Recent advances in UASs provide us with an excellent avenue for obtaining more frequent profiles of various atmospheric quantities. A relatively inexpensive, lightweight (sometimes <1 kg) UAS can make a variety of basic atmospheric measurements while flying pre-defined flight patterns. The cost of some of these systems is only marginally greater than a standard radiosonde package, yet their ability to be reused allows for a much larger return on investment. These lightweight systems can obtain basic meteorological information about, for example, temperature, humidity, and winds and also somewhat more exotic quantities such as turbulence intensity and aerosol concentrations, and can be directed to sample specific areas laterally and vertically to quantify three-dimensional spatial variability or provide fine-scale measurements in areas of particular interest. Such systems are ideal for use in routine profiling of the lower arctic atmosphere. In addition, larger (between 1 and 23 kg) UASs have the ability to carry heavier and more complex instrumentation and potentially fly for extended time periods. Such platforms are suited for more detailed measurement of cloud and aerosol properties, radiation, and more.

Despite the potential for UASs in atmospheric measurement, to date only limited flights have occurred. This is particularly true at higher latitudes, where only a small number of UAS experiments have been carried out (e.g., Curry et al. 2004; Cassano et al. 2010). These experiments, along with a recent report by the Arctic Monitoring and Assessment Program (AMAP) (Crowe et al. 2012) provide examples of some of the types of measurements can be made from UASs at high latitudes. To capitalize on these new technologies, we propose to carry out a UAS-based measurement campaign that will provide a high-quality scientific dataset to the ARM and Atmospheric System Research (ASR) communities, as well as demonstrate the capabilities and potential for routine UAS use in atmospheric research.

3.0 Campaign Objectives

Improved understanding of arctic atmospheric processes, in particular those related to clouds, aerosols, and radiation, will benefit from measurement capabilities that have, to date, not been employed. The

Evaluation of Routine Atmospheric Sounding Measurements using Unmanned Systems (ERASMUS) project aims to take the necessary first steps for obtaining these measurements. As part of this project, we propose to carry out UAS flights at Oliktok Point over 2, 2-week periods during 2015 and 2016. These flights will be designed to meet two primary objectives:

1. *Collection of 2-week datasets that provide complimentary measurements to those obtained by the third ARM Mobile Facility (AMF3). AMF3 is deployed at Oliktok Point during the proposed ERASMUS period*. UAS-based profiles of key atmospheric thermodynamic properties (e.g., temperature, relative humidity, etc.) will provide context for surface and remote-sensing measurements from AMF3, creating a well-profiled case study period through which to better understand scientific questions outlined in the following section. In addition, profiles of advanced measurements (e.g., broadband radiation, aerosol concentrations) provide sorely needed information on the vertical variability of these properties, as well as datasets that can be used to evaluate remote-sensor retrieval algorithms.
2. *Demonstration of UAS capabilities in obtaining measurements relevant to the ARM Facility and ASR program, particularly for improving our understanding of arctic clouds and aerosols*. Routine flights measuring basic atmospheric quantities such as temperature, humidity, winds, and aerosol concentration will be completed. In addition, additional aircraft will be used to demonstrate ARM-specific measurement capabilities. These include basic measurements of aerosol size distribution and broadband radiation. Instrumentation to be deployed during the ERASMUS campaign is described in Table 1.

Table 1. Description of instrumentation to be deployed during the ERASMUS campaign.

Platform	Instrument	Measurements	Details
DataHawk	Texas Instruments ADS1118	temperature	
	Honeywell HIH-5030	humidity	~5 s response time
	MEAS MS5611	pressure	
	Custom cold wire	fast temperature	100 Hz update
Pilatus	SPN-1 Pyranometer (broadband shortwave radiometer)	broadband shortwave radiation	400-2700 nm, three sensors (2 up, 1 down), can separate direct/diffuse, does not fly with CGR-4
	CGR-4 Pyrgeometer (broadband longwave radiometer)	broadband longwave radiation	4.5 to 42 microns, two sensors (1 up, 1 down), does not fly with SPN-1
	Printed Optical Particle Spectrometer (POPS)	aerosol size distribution	150-2500 nm
	NCAR Custom Dropsonde PTH module (including Vaisala RSS904 sensor package)	temperature, humidity, pressure	
	VectorNav RS-200	aircraft attitude	co-mounted with SPN-1s for southwest attitude correction

4.0 Related Science Questions

Measurements obtained from UAS during ERASMUS will target several outstanding problems in our understanding of the Arctic's atmosphere. While the statistics obtained over a 2-week period will not provide a statistical sample size sufficient to adequately address open questions, it is believed that 2 weeks of high-frequency profiles will fill some crucial gaps in our current understanding and enhance our observational network to establish a well-informed case study period. The measurements will guide future efforts within several active areas of research in the ASR community, with key research questions outlined here:

1. *How do low-level temperature and moisture evolve during transitions between clear and cloudy atmospheric states?* Several recent papers (e.g., Morrison et al. 2012, Stramler et al. 2011) have discussed the importance of understanding conditions supporting the transitions between radiatively clear and radiatively opaque (cloudy) conditions in the Arctic. Typical 12-hour radiosonde launches often provide insufficient coverage during the transitions between these states. This lack of coverage has left unanswered questions surrounding the relative roles of local and advected temperature and moisture, and the evolution of the atmosphere before, during, and after initial cloud formation, as well as during cloud dissipation. UASs can provide more frequent profiling of the lower atmosphere to better understand the evolution of temperature, humidity, pressure, and other factors relevant to low cloud life cycle.

2. *How do aerosol properties vary with height at high latitude locations?* Some of the largest questions surrounding our understanding of mixed-phase cloud properties involve understanding the sources and sinks of aerosol particles. During winter and spring months, when sea ice covers much of the Arctic Ocean, it seems that there are limited surface sources of cloud condensation nucleation (CCN) and ice forming nucleation. Numerical studies (e.g., Fridlind et al. 2012) have raised interesting questions surrounding the aerosol budget in mixed-phase cloud environments. In addition, understanding of aerosol-cloud interactions (e.g., Garrett and Zhao 2006; Lubin and Vogelmann 2006) has often relied upon aerosol measurements taken at or near the Earth's surface. Because of the potential for strong stratification of the lower arctic atmosphere, the representativeness of surface-based aerosol measurements has to be evaluated, and the principal investigator (PI) currently has an ASR-funded project in this area of research. UAS measurements will provide us with basic (e.g., concentration of large particles) information on aerosol in the lower arctic atmosphere.

3. *How well do current remote-sensing retrievals perform in the arctic environment?* Frequent profiles of lower atmospheric thermodynamics will be helpful in assessing the accuracy of new ARM PI products designed to evaluate atmospheric mixing state (PI: Shupe). Additionally, aerosol and radiation profiles can provide insight into the performance of products derived through a combination of several measurement-based retrievals and modeling tools (e.g., broadband radiative heating rates through broadband heating rate profiles).

4. *What is the spatial variability of heat and moisture fluxes from the surface over ice and land surfaces?* Low-level horizontal legs will provide us with near-surface temperature, humidity, and wind, as well as surface skin temperature, allowing us to estimate bulk surface fluxes and provide information on the spatial homogeneity of such fluxes over both the sea ice and tundra surfaces at sub-GCM-grid scales.

These specific science questions and other gaps in our understanding of lower arctic atmospheric processes result in part from insufficient sampling of the lower atmosphere. Long-term UAS-based profiling of basic meteorological quantities, as well as more advanced measurements of clouds, radiation, and aerosols, will, in the future, result in cross- cutting data sets that help inform active areas of research within the DOE ASR program. ERASMUS activities are designed in part to evaluate the collection of these measurements on a routine basis, demonstrate capabilities, and provide guidance for future UAS-based campaigns. Specific criteria to be evaluated during ERASMUS include:

1. *The influence of environmental conditions on routine UAS operations at Oliktok Point*. Clouds, winds and extreme cold can all prevent routine flight activities. We propose to perform a limited scope evaluation of these parameters for two classes of UASs: 1) low-cost, ultra-lightweight DataHawk vehicles, and 2) medium-cost, lightweight systems (Pilatus). One of the major concerns for UAS operations is airframe and/or instrument icing. Use of the relatively inexpensive, small, and lightweight DataHawk will allow us to investigate the threshold for safe UAS operation around Oliktok without fear of significant financial loss, environmental impact, or threat to structures. While the larger UAS (Pilatus) will provide enhanced instrumentation support, they also have additional operational constraints. This tradeoff will be investigated in the specific context of the Oliktok Point operating environment.
2. *The required number of personnel for routine flight activity*. At present, operation of the proposed UAS requires two operators per aircraft. While this number is already less than that required for larger UASs such as Aerosondes, Mantas, and ScanEagles, it may decrease further with future advances in UAS deployment and recovery. The need for two operators results in significant financial cost and need for living space. We will evaluate the possibility of using alternative sampling strategies and personnel workloads in an attempt to optimize deployment of all UAS platforms.
3. *Operational considerations of the Oliktok Point site itself*. We will provide an assessment of the current operational obstacles to routine UAS activities. This includes evaluation of current power/lighting/heat infrastructure, currently available bunk space and living facilities, safety aspects, and additional infrastructure necessary for flight operations (communication, launch/landing space, etc.).

5.0 Campaign Timing and Location

All campaign UAS flights will take place at Oliktok Point, Alaska. The first phase of ERASMUS will consist of 2 weeks of DataHawk flights and will take place during June/July 2015. The second phase will consist of 2 weeks of Pilatus flights and will take place in April 2016.

5.1 DataHawk

The DataHawk UAS is a small-scale (1 m wingspan), lightweight (<1 kg) unmanned aircraft designed and constructed at the University of Colorado Boulder (Figure 1). The current version of this aircraft has an endurance of approximately 1 hour, and operates at a cruise speed of approximately 20 m/s. This aircraft carries a limited but useful set of instruments for obtaining information on atmospheric thermodynamics. Included are custom and coldwire temperature sensors, a humidity sensor, a pressure sensor, a downward looking infrared sensor for measuring surface temperature, and instrumentation for estimating wind speed and turbulence.

Figure 1. DataHawk UAS shown on top of its shipping container.

The DataHawk is capable of fully autonomous operation from launch to landing. The system is guided by the CUPIC autopilot during flight, allowing for the establishment of preprogrammed waypoints to aid navigation.

5.2 Pilatus

The Pilatus UAS is a converted kit aircraft with a 3.2-m wingspan (Figure 2). It is capable of operating at up to 55 lbs., including payload. The aircraft is guided by a Piccolo autopilot and powered by an electric motor. This aircraft, when loaded, operates at around 50 knots airspeed and has a limited endurance of around 15 minutes. For this campaign, the aircraft will carry scientific instrumentation in three different configurations. The first configuration (Printed Optical Particle Spectrometer [POPS] only), includes the POPS instrument, designed and constructed at the National Oceanographic and Atmospheric Administration’s Earth System Research Laboratory, along with an NCAR-developed dropsonde package that includes Vaisala’s RSS904 sensor package to collect information on atmospheric thermodynamics (hereafter “PTH module”). With this configuration, extra batteries can be carried to extend the flight duration to around 30 minutes. A second payload configuration (i.e., shortwave) will include the POPS, the PTH module, three Delta-T SPN-1 broadband pyranometers, and a high-grade inertial measurement unit to assist with tilt corrections for changes in aircraft attitude.. This payload will feature two upward looking SPN-1s, one with the manufacturer’s shading pattern and one without to allow for separation of direct and diffuse radiation, as well as a downward looking sensor. Finally, the third payload configuration will feature the POPS, the PTH module, and two Kipp and Zonen CGR-4 pyrgeometers (broadband longwave radiometers). This will include one upward- and one downward looking CGR-4.

Figure 2. The Pilatus UAS shown equipped with the PTH module (white, on wing), SPN-1 Shortwave Pyranometers (two upward and one downward looking), and the POPS Aerosol Spectrometer (in windshield).

6.0 Sampling Considerations and Strategies

Because of the nature of the measurements being made, the two phases will employ different sampling strategies. The DataHawks will be flown hourly, weather permitting, for 12 hours per day over the 2-week campaign period. These flights will consist of a consistent pattern involving an over land spiral ascent to either the lowest elevation of the cloud base or to 2 km (Figure 3). Once at maximum altitude, the DataHawk will perform a level flight leg to a preset waypoint offshore, and then it will initiate a spiral descent back toward the surface. Both the ascent and descent will be executed at a controlled rate around 1 m/s. When it reaches an altitude of 30 m above the surface, the DataHawk will return to the waypoint marking its original ascending spiral and return home. After landing, the battery will be replaced, and after an hour has passed since the previous launch, the aircraft will be deployed again to execute the same sampling pattern.

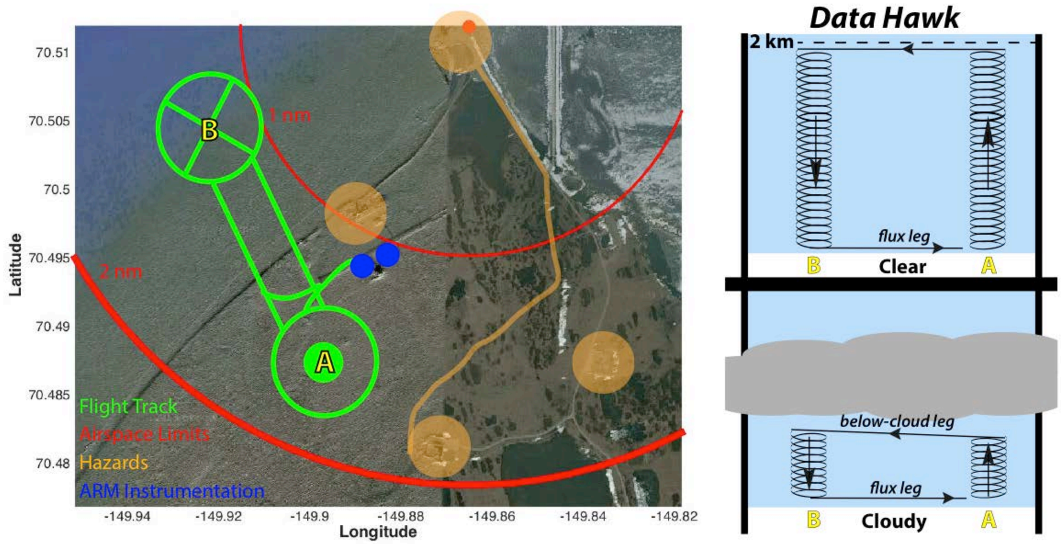

Figure 3. Proposed flight pattern for the DataHawk UAS.

When carrying radiometers, the Pilatus aircraft will be flown in an extended racetrack pattern to maximize the time spent with level wings (Figure 4). This is critical for making usable measurements of atmospheric radiation, as tilt correction can be done for pitch/roll angles of up to 10 degrees from level. Initially, the aircraft will climb to 600 m above the ground surface and then begin following present waypoints to execute the racetrack pattern. After flying level for 30 s, the aircraft will descend by 50 m, and continue the racetrack pattern. This sequence will be repeated every 30 s until the aircraft is at 50 m above the surface, at which point it will likely have to return to land. When not carrying radiometers (i.e. aerosol and thermodynamics only), we will not be constrained by the need for level wings and will instead perform slow spiral ascent/descent sampling to obtain a more continuous profile of aerosol size distribution and thermodynamics. All Pilatus flights will be conducted over land to most directly compare with the complementary measurements obtained from the AMF3.

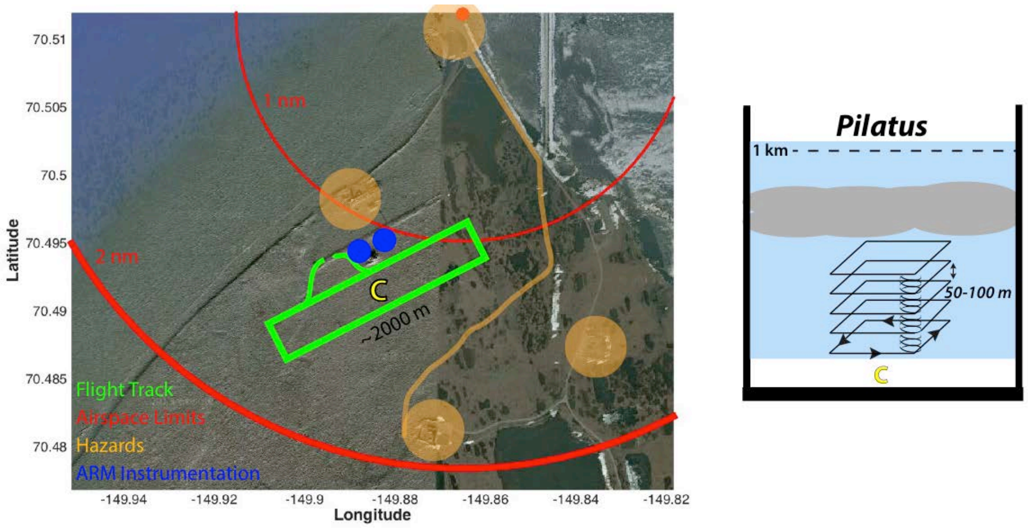

Figure 4. Proposed flight pattern for the Pilatus UAS.

7.0 Related Research and Relevancy to the Office of Biological and Environmental Research

Research topics directly connected to measurements obtained during ERASMUS are reviewed in the above in Section 4. Research to understand mixed-phase cloud lifetime, lower arctic atmospheric stratification, vertical distribution of aerosol at high latitudes, arctic aerosol-cloud interactions, surface energy balance, remote sensing retrievals, and broadband radiative heating rate profiles will all benefit from measurements made during the ERASMUS campaign. Currently, efforts to understand scientific questions related to the topics listed above are supported through the ASR working groups. Specifically, scientific question numbers 1, 2, and 3 described in Section 4 are directly relevant to scientific questions raised within the ASR Cloud Life Cycle Working Group's subgroup on mixed-phase cloud processes and cloud phase. The proposed measurements will help to better constrain budgets relevant for understanding of mixed-phase cloud formation and lifetime (moisture budget, aerosol budget, radiation budget).

In addition to the research topics listed in Section 4 and in previous discussions in this science plan, routine UAS measurements have the potential to aid progress across a wide range of topics relevant to the ASR program. Because ERASMUS is in part a demonstration experiment designed to not only collect data, but also to break ground for future UAS-based measurement campaigns, it is important to weigh the potential contributions to the ASR program that may result from this experiment. Examples of specific research areas currently listed as ASR focus topics that can further benefit from future UAS flights are listed below.

From the Cloud Life Cycle Working Group

- *Role of clouds and precipitation in establishing and limiting stratification in the Arctic's lower troposphere.* Currently, profiling of atmospheric temperature is done at 12-hour intervals. Twelve-hourly sampling leaves too much time open for interpretation to successfully answer this question from an observational perspective.
- *Factors that control cloud phase (super-cooled liquid only, pure ice, or mixed- phase).* Frequent thermodynamic and aerosol measurements in and around clouds are a key component of addressing this question. Currently, such high-frequency, in situ measurements are not available.
- *How arctic cloud properties respond to climate changes such as decreases in sea ice concentration, increases in atmospheric temperatures, changes in circulation patterns, etc.* Understanding this topic requires accurate model parameterizations of arctic clouds. Increased in- and near-cloud measurements will help to improve our physical understanding of the cloud system.
- *Ice nucleation mechanisms important in cold clouds with and without liquid water.* While it is unlikely that ice nucleus counters will soon fly on UAS, profiles of other aerosol properties (size, number, composition), together with remote sensing measurements can help us to make progress on understanding ice nucleation.

From the Cloud-Aerosol-Precipitation Interactions Working Group

- *Factors determining the CCN background concentration (what processes create them, in what regimes, and how are they transported to the cloud level).* With CCN counters (e.g., Roberts and Nenes 2005) now available in miniaturized form, we can collect, on a routine basis, profiles of CCN activity, which will help to address several of these issues. In particular, routine profiles would be helpful for addressing aerosol pathways to cloud height.

- *Factors through which entrainment influences the impact of aerosol on clouds*. With UAS-based measurements of turbulence and aerosol concentrations, we can begin to assess the pathways through which aerosols make their way into clouds.
- *Controlling factors that determine the spatiotemporal influence of aerosol on precipitation*. In addition to being able to collect routine profiles, small-scale UAS can potentially be used to obtain horizontal transects over medium-range (100-km) distances. This would help in the collection of spatial distributions of aerosol concentrations around ARM scanning radar systems.
- *Importance of vertical transport in cloud updrafts and downdrafts, aqueous chemistry in cloud drops and scavenging by precipitation in the life cycle of the aerosol as a function of particle size*. UASs will allow us to spatially map aerosol concentrations and sizes on a routine basis to help address these questions.

From the Aerosol Life Cycle Working Group

- *Role of absorbing aerosol on heating rate profiles, atmospheric circulation, cloud development, and precipitation.* Small UASs can collect aerosol and radiation measurements to help address these questions.
- *Quantifying and parameterizing the dependence of aerosol optical properties on relative humidity.* Profiles of relative humidity in the vicinity of surface-based lidar systems, as well as UAS-based optical measurements, can help to address this question for natural aerosols.
- *Cloud processing of aerosol (aqueous-phase chemistry, droplet coalescences, and wet removal).* Frequent near-cloud measurements of aerosol optical properties could be obtained using UASs and would be helpful for assessing the influence of clouds.

Supporting and facilitating research completed within the DOE ASR program is a critical role for the ARM Climate Research Facility. It is through this research that ACRF can carry out its stated mission of studying and monitoring the Earth system. Clouds and aerosols along with the interactions between them and their role in the Earth's radiative budget are among the most poorly understood and modeled components of the Earth system. The types of UAS-based measurements proposed here will facilitate improvement of our understanding of these critical Earth system components by providing vital data for analysis and model studies. These studies will subsequently foster the advancement of predictive understanding of the Earth's climate and environmental systems through improvement of GCMs, thereby aiding in addressing the DOE BER CESD mission to improve climate data and models for policy-makers.

Routine UAS measurements such as those proposed for the ERASMUS campaign will help to foster advancements addressing several of ARM's stated priorities. These include the following:

- *Full exploitation of new American Reinvestment and Recovery Act of 2009 instrumentation and capabilities of all ARM facilities.* In situ measurements from the UAS platforms will aid in the improvement of retrieval algorithms for these new instruments. This will improve their utility.
- *Deployment of the third mobile facility at Oliktok, Alaska, coupled with regular deployments of small, unmanned aerial vehicles for in situ measurements, in order to launch a multi-year effort to provide*

critical cloud and aerosol properties over land, oceans, and sea ice. The activities proposed here are essentially directly described by this specific goal.

- *Coupling of data from the Barrow and Oliktok Point sites to develop grid-scale products for improving model representation of arctic atmospheric dynamics, cloud, aerosol, and precipitation processes.* The three-dimensionality of UAS measurements moves us beyond the "soda-straw" perspective and allows evaluation of spatial heterogeneity on several length and time scales. Subsequent UAS activities, in part guided by lessons learned during the ERASMUS campaign, may allow for direct connection of the Barrow and Oliktok Point sites through routine sampling flights between them.
- *Bridging the atmospheric and modeling communities to optimize the collection and reporting of observations in ways that best address the collective needs of these communities*. Several of the science questions discussed earlier come directly from previous modeling activities. Specifically, understanding the vertical distribution of aerosol properties, the vertical distribution of temperature and moisture, the transition from clear to cloudy arctic states, and the role of moisture inversions in cloud formation and life cycle are all research avenues derived from modeling studies. Observations taken during the ERASMUS campaign will additionally help to provide a highly detailed case study period to study these processes and others with observational and modeling tools.

Finally, this activity directly addresses the three types of activities outlined in the ARM Aerial Vehicle Program science document, namely the following:

- *Routine observations of cloud, aerosol and radiative properties*. ERASMUS will make these measurements at Oliktok Point, providing detailed information to support AMF3 surface-based measurements.
- *Participation in campaigns designed to contribute to our fundamental understanding of cloud properties and effects*. ERASMUS specifically targets processes relevant for low-level mixed-phase clouds, including aerosol and thermodynamic processes.
- *Foster an instrument development program whereby miniaturized in situ and remote-sensing instruments will be purchased or developed, the small size of the instruments ultimately allowing them to be used on UAS platforms*. A part of the ERASMUS activity will involve the integration of miniaturized instrumentation onto UAS platforms, including basic meteorological, aerosol, and cloud instruments.

8.0 ARM Resources Required

- Data/internet connection at Oliktok Point
- Power for charging UAS equipment at Oliktok Point
- Access to a tundra vehicle for recovery of aircraft (if necessary/possible)
- Access to storage area for aircraft and equipment
- Room and board during the ERASMUS campaign
- Federal Aviation Administration coordination for activation of airspace and communication of flight activities

- Bear guards for periods of outdoor operations
- Operation of AMF3
- Near real-time access to AMF3 measurements (when possible)
- Guidance in the safety review process
- Instrument loans (SPN-1 and CGR-4).

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