U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-ARM-18-021

Profiling at Oliktok Point to Enhance Year of Polar Prediction Experiments (POPEYE) Science Plan

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May 2018

ARM

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May 2018

Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Executive Summary

The arctic region is rapidly evolving, and enhanced predictive capabilities, for both weather and climate, are urgently required. Therefore, the international community has formulated plans for the execution of an extended period of focused observations and modeling of the arctic environment, dubbed the "Year of Polar Prediction" or YOPP. The YOPP will feature "special observing periods" (SOPs), with the first occurring in the spring of 2018, and a second during the late summer and early fall. This project deploys additional U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) facility resources to Oliktok Point, Alaska during the second three-month special observing period (1 July 2018-30 September 2018). These resources include additional radiosondes (1 more per day), ARM-operated unmanned aircraft (DH2) and ARM-operated tethered balloon systems (TBS). These instruments will conduct routine profiling activities over the course of the SOP to obtain measurements of atmospheric thermodynamic structure, cloud and precipitation properties, and aerosol properties, enhancing the measurements obtained from the third ARM Mobile Facility at Oliktok Point (AMF3). We anticipate that these measurements will be used for a variety of purposes, including: 1) to conduct detailed studies of arctic cloud and aerosol processes; 2) to inform YOPP modeling efforts through real-time availability for assimilation into operational and research analysis products; 3) to evaluate and improve retrieval algorithms involving ARM remote sensors; 4) to evaluate and improve a variety of modeling tools being used to forecast arctic weather and climate; and 5) to initialize and evaluate simulations associated with a potential arctic large-eddy simulation (LES) framework similar to the ongoing LES ARM Symbiotic Simulation and Observation (LASSO) project.

Acronyms and Abbreviations

AAF	ARM Aerial Facility
AERI	atmospheric emitted radiance interferometer
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASR	Atmospheric System Research
BER	Office of Biological and Environmental Research
CAFS	Coupled Arctic Forecasting System
CESD	Climate and Environmental Sciences Division
CPC	condensation particle counter
CU	University of Colorado
DH2	DataHawk2
DOE	U.S. Department of Energy
DTS	distributed temperature system
ECMWF	European Centre for Medium Range Weather Forecasts
ESM	earth system model
IASOA	Integrated Arctic Systems for Observing the Atmosphere
IOP	intensive operational period
LASSO	LES ARM Symbiotic Simulation and Observation
LES	large-eddy simulation
MOSAIC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
POPEYE	Profiling at Oliktok Point to Enhance YOPP Experiments
POPS	portable optical particle counter
PPP	Polar Prediction Project
SLWC	super-cooled liquid water content
SOP	special observing period
TBS	tethered balloon system
UAS	unmanned aerial system
UTC	Coordinated Universal Time
WWRP	World Weather Research Programme
YOPP	Year of Polar Prediction

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1.0 Background

Recent decades have seen notable shifts in arctic climate (Serreze et al. 2007; Screen and Simmonds 2010). Reductions in sea ice (Maslanik et al. 2011; Comiso et al. 2008), evident as an integrator of a warming arctic atmosphere (Dobricic et al. 2016; Graversen et al. 2008) and evolving surface energy budget (Mayer et al., 2016; Hudson et al. 2013), act to enhance absorption of solar radiation at the surface due to a dramatic shift in surface albedo, potentially enhancing arctic warming. Sea-ice reductions also present opportunities for commerce, including natural resource extraction, shipping, and fishing (Smith and Stephenson 2013; Ho 2010). Finally, these changes have direct implications for border security due to reduced difficulties with navigation in arctic waters.

In recognition of the importance of these changes and our need to be able to predict and understand them, the World Weather Research Programme (WWRP) established the Polar Prediction Project (PPP). As a part of this project, an extended period of coordinated and intensive observations has been developed in conjunction with focused modeling activities. This period has come to be known as the Year of Polar Prediction (YOPP), and it targets the improvement of prediction capabilities across a wide variety of time scales, from hours to seasons. The core phase for this activity gets underway in mid-2017, and lasts through mid-2019. During 2018, YOPP will feature two special observing periods, including one spring and one late summer (1 July 2018 to 30 September 2018) period. Following the core phase will be a three-year consolidation phase, during which a variety of experiments and analysis projects will use the various data sets collected during the core phase to evaluate and improve models, conduct data denial experiments, and evaluate the state of polar prediction.

This document provides a science plan for an intensive observation period (IOP) at the ARM Mobile Facility (AMF3) currently deployed to Oliktok Point, Alaska as a contribution to YOPP. This IOP, titled “Profiling at Oliktok Point to Enhance YOPP Experiments” (POPEYE), includes high-frequency profiling of thermodynamics, clouds, and aerosols using ARM’s unmanned aerial capabilities (DH2 and TBS). POPEYE will take place during the second of the two[1] identified arctic YOPP SOPs, which will involve expanded measurements across the region. The late summer timing of this SOP will witness extensive melting of arctic sea ice as it moves to a seasonal minimum extent. Specifically, at Oliktok Point, this period will likely produce a variety of boundary-layer states. This includes the potential for stable boundary layers developed offshore during the early portion of the observing period when near-shore sea ice is likely to still be present. Later, this period will feature extensive open water between the shore and sea ice, contributing to the development of convective boundary layers as air flows from the ice over the water surface and advects past Oliktok Point. Additionally, the land surface will be snow- and ice-free during this time, resulting in development of shallow convective boundary-layer states over the land surface and associated shallow convective cloud structures. Generally, clouds observed during this period will likely include both liquid- and mixed-phase clouds. From an aerosol perspective, this period will provide access to a variety of potential sources, including the ocean surface, biomass burning events in Alaska, local industrial activity, and the land surface.

[1] The possibility of a third YOPP SOP associated with the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAIC) campaign is currently under discussion.

2.0 Scientific Objectives

Based on the input of the global weather and climate modeling communities, YOPP has established a set of detailed modeling priorities. A central goal of POPEYE is to provide unique perspectives on the atmosphere to support follow-up studies under YOPP. Below, we list the YOPP priority topics most likely to be informed by POPEYE measurements:

1. Boundary layer including mixed-phase clouds
2. Sea ice modeling
3. Physics of coupling, including snow on sea ice
4. Model validation and intercomparison
5. The stratosphere
6. Chemistry, including aerosols and ozone.

2.1 Science Questions

Under these topics, there are a variety of questions to be answered by the scientific community. Below we outline some outstanding questions that connect YOPP and the Oliktok Point Site Science Team, and the ways in which POPEYE measurements can be used to help address them.

1. **Boundary layer including mixed-phase clouds**: The lower-atmospheric thermodynamic observations provided by the DataHawks and tethered balloon will provide one of the most detailed data sets of arctic summertime boundary layers ever collected. The measurements themselves will provide detailed insight into the structure of the boundary layer and its evolution and will additionally provide a means of validating retrieval algorithms from remote sensors (e.g., atmospheric emitted radiance interferometer [AERI], Raman lidar) under a variety of meteorological and cloud cover scenes to support future model improvement and validation efforts. These lower-atmospheric measurements, in conjunction with information from ARM remote sensors and TBS-deployed super-cooled liquid water content (SLWC) and aerosol measurement systems, will provide detailed information of liquid-containing cloud properties and the environment that sustains them. Finally, this suite of observations will provide critically needed measurements to directly support the YOPP goal of pursuing an integrated modeling framework to connect cloud, boundary layer, and surface energy exchange schemes through LES-based development. Specific questions that these measurements can help address include:
   a. Why is liquid water formation favored in environments as cold as -30 C?
   b. To what extent can we use surface-based aerosol measurements as a proxy for in-cloud aerosol in the arctic atmosphere?
   c. How do aerosol particles impact precipitation susceptibility in high-latitude, liquid-containing clouds?
2. **Sea ice modeling**: Measurements provided as part of POPEYE will complement a variety of observational efforts occurring during YOPP, and will be used directly by our team to advance our ability to predict sea ice variability at timescales from 0 to 10 days. This will be completed as part of our validation effort to improve the Coupled Arctic Forecasting System (CAFS), an in-house version

of the Regional Arctic System Model currently being developed by the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Division. This model represents a fully coupled, ice-ocean-atmosphere regional prediction system being used for forecasting sea ice at short timescales. This model will be run in ensemble mode starting in fall, 2017. Specific questions that these measurements can help address include:

   a. How well does CAFS capture the atmospheric forcing in the coastal Beaufort Sea region, including surface radiation and momentum fluxes?

   b. What is the predictability timescale in this part of the world and to what extent is this impacted by having a fully coupled model?

3. **Physics of coupling, including snow on sea ice**: While the connection to this objective is not obvious, one of the topics listed under this YOPP objective is the development of improved schemes of moist convection associated with unstable boundary-layer conditions occurring with cold-air outbreaks. The lower atmospheric profiling suggested can provide measurements of the structure of the boundary layer at a known distance from a sharp temperature contrast (e.g., the coast, or the ice-ocean interface). Specific questions that these measurements can help address include:

   a. How do turbulent fluxes of heat, moisture, and momentum help to shape shallow convective boundary-layer clouds?

   b. How does the proximity of sea ice influence the structure of the lower atmosphere in off-ice flow conditions?

4. **Model validation and intercomparison**: The detailed measurements provided as part of POPEYE will provide a highly detailed data set that can be used for evaluation of model performance. Specifically, the detailed structure and evolution of the boundary layer and lower troposphere, as well as the additional insight provided into cloud properties, are worth investigating across a variety of model products (e.g., reanalyses, weather forecast models, coupled regional forecast models, global climate models). Additionally, the measurements collected will provide detailed constraints on the initial and boundary conditions for intercomparisons of single-column and large-eddy simulation models that could be constructed. Specific questions that these measurements can help address include:

   a. How well do modern reanalyses, and short- and long-timescale forecast models, simulate the structure of the lower arctic atmosphere in summer?

   b. To what extent do these model products correctly reproduce liquid- and ice-phase partitioning in summertime arctic clouds?

   c. Can models correctly simulate the timing (for weather models) and statistics (for climate models) of arctic convection, and how are these limited convective events different than those at lower latitudes?

5. **The Stratosphere**: The increased frequency of radiosonde launches will provide an increased level of detail for stratospheric observation. This is particularly interesting in conjunction with similar increases in radiosonde launch frequency at other sites, such as those in the Integrated Arctic Systems for Observing the Atmosphere (IASOA) consortium of observatories, or over the Beaufort Sea from planned ship activities such as those to be carried out by the Japanese research vessel *Mirai*. Specific questions that these measurements can help address include:

   a. What controls the temperature of the arctic stratosphere in summer?

6. **Chemistry, including aerosols and ozone**: The aerosol measurements that will be provided by the ARM tethered balloon system include information on particle number concentration, size distribution, scattering, and (hopefully) composition. Profiling these properties, even at low altitudes, will provide a rare opportunity to evaluate stratification of aerosol properties in the arctic atmosphere over an extended, nearly continuous period and in coordination with detailed boundary-layer measurements. Specific questions that these measurements can help address include:
   a. Are local emissions from Prudhoe Bay industrial activities distributed evenly through the lower atmosphere?
   b. To what extent do clouds process and redistribute aerosols vertically through the lower arctic atmosphere?
   c. How do the sizes and number of particles differ between on- and offshore wind regimes, and what is the potential impact of these differences on clouds?

Admittedly, the main motivation for POPEYE is to develop a widely usable community resource. With a few exceptions, many of the activities addressing YOPP objectives described above will not be carried out directly by the proposing team. Part of the success of POPEYE will depend on the ability of our team to advertise this project to the greater arctic modeling and observational communities, highlighting unique elements unlikely to be available through other YOPP measurement campaigns. We are well positioned to advocate for the use of such data through our community leadership roles and extensive involvement in YOPP-centric activities, and believe that we can generate significant interest in the use of a data set such as would be collected during POPEYE.

Having said this, however, our team will conduct a fair amount of original research with POPEYE data through already funded mechanisms. Data collected under POPEYE will be used for modeling activities related to understanding mixed-phase clouds and boundary-layer evolution in the tail end of our team's funded DOE Atmospheric System Research (ASR) project to serve as the Oliktok Point site science team. Specific objectives that would be covered under the Oliktok site science project (***in bold, italic type***), as laid out in our initial proposal, include:

1. ***Understanding clear-cloudy transitions for arctic stratiform clouds***: The regular profiling will capture several clear-to-cloudy (and vice versa) transitions, allowing us to build statistics on the dynamic and thermodynamic regimes supporting such transitions. The high temporal frequency of these profiles will provide us with continuous updates on transition periods, not obtainable with routine radiosonde launches.
2. ***Understanding aerosol-cloud interactions for high-latitude clouds, including mixed-phase scenarios***: The combined profiling of super-cooled liquid water content, thermodynamics, and aerosols will provide a unique data set for evaluating the influence of aerosol particles on clouds. The unique offering of aerosol property and liquid water content profiles, when coupled with the information from surface-based AMF3 sensors, should help us to develop key case studies on this topic.
3. ***Characterization of aerosol properties in the Oliktok Point environment***: The aerosol profiling will develop statistics on correlations between surface and cloud-height aerosol particles. Additionally, it will provide information on the vertical distribution of local aerosol plumes from Prudhoe Bay industrial activities.

4. ***Characterization of cloud properties and processes at Oliktok Point and comparison with properties observed at Barrow***: Again, the profiling of super-cooled liquid water content should provide insight into key properties, such as adiabaticity of the clouds. Additionally, should capabilities to conduct further microphysical measurements using Unmanned Aerial Systems (UAS)/TBS be available by fall of 2018, this would provide additional insight into the microphysical properties of clouds, making these data very relevant for the development and execution of modeling case studies and for direct comparisons with ground-based cloud property retrievals.
5. ***Advancement of the Oliktok Point facility in the international research community***: As discussed above, we feel this is critical to the success of POPEYE. The YOPP provides us with a terrific platform to further put Oliktok Point on the map when it comes to arctic observatories. Development of a robust data set that integrates with such a widely recognized international activity will be a key step toward expanding the use of ARM data from Oliktok Point internationally. As part of this effort we will work to incorporate Oliktok Point into the collection of YOPP fixed verification sites where high-resolution model data will be routinely produced during YOPP to enable assessment of these operational models using the site observations.

In addition to the work done as part of the ongoing Oliktok Point site science effort, team members are involved with the development and evaluation of a fully coupled regional model for short-term sea-ice prediction (CAFS). This model, based on the Regional Arctic System Model (RASM) originally developed under funding from DOE and the National Science Foundation (NSF), includes components covering the atmosphere and ocean, as well as ice and land surfaces. Measurements collected will be used to evaluate and improve the atmospheric component of this modeling system through process studies, and the evaluation of specific parameterizations related to boundary-layer structure, atmospheric mixing, turbulence, and microphysics.

Similarly, measurements obtained during POPEYE will be used for the development of process and case studies within the DOE ASR community. Specifically, these measurements can inform and support community-wide studies related to boundary-layer structure, cloud phase, cloud formation and lifetime, and aerosol processes. These measurements can also be used to evaluate retrieval products being developed using ARM instruments. Our team is well positioned to advocate for such efforts, with principal investigator (PI) de Boer leading the High-Latitude Processes working group within ASR and several Oliktok Point site science team members being involved with retrieval development and evaluation.

Finally, there have been recent discussions within ARM about the potential for extending the current “LES Symbiotic Simulation and Observation” (LASSO) workflow to arctic ARM sites. The extended measurements associated with POPEYE, including frequent profiling of the thermodynamic structure of the atmosphere, in conjunction with the additional observational and modeling work that will be conducted during this focused portion of the YOPP, will provide a nice three-month test period for evaluating an arctic LASSO project. Not only would there be additional measurements that can be used for model evaluation, but these measurements could also be used for development of initial and boundary conditions for arctic LASSO simulations. Additionally, engagement of operational modeling centers such as the European Centre for Medium Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP), and the United Kingdom Meteorological Office (UKMO) to YOPP should provide access to additional operational analysis data sets and products, required for model initialization.

In conclusion, YOPP provides an opportunity to contribute to, and leverage, a wide-reaching international coordinated effort to improve understanding of arctic weather and climate. Such opportunities are rare due to the tremendous amount of support required to coordinate measurements across such an international region. Integration into such an effort enables widespread use of measurements from the Oliktok Point facility for the purposes of improving our fundamental understanding of processes central to arctic atmospheric states, evaluation and improvement of weather and climate models, and operational inclusion of measurements into numerical weather prediction at regional and global scales. For example, extra POPEYE radiosondes will feed into a broader YOPP activity associated with understanding data assimilation into operational models, and facilitate studies into the impact of enhanced arctic observations on predictions of lower-latitude weather (e.g., Jung 2014; Inoue et al. 2015). Through POPEYE, DOE is making a unique contribution by enhancing its routine operational measurement framework at Oliktok Point, thereby increasing the utility and visibility of the data set collected using the AMF3 to provide critically needed insight into the weather and climate of arctic Alaska.

3.0 Measurement Strategies

Operationally, this period should provide one of the more quiescent periods, featuring lower wind speeds and warmer conditions than the spring and fall periods. This is important for conducting routine operation of the unmanned systems, and warmer temperatures during this time reduces stress on operators. Additionally, extensive daylight during these months provides flexibility in operating times, expanding the opportunity to conduct sampling and reducing danger associated with wildlife encounters during nighttime UAS and TBS operations and launching activities. Below, we provide an overview of how the various assets related to this campaign will be deployed for POPEYE.

3.1 Location 1 (AMF3)

The third ARM Mobile Facility (AMF3) will be operating in a routine mode at Oliktok Point during POPEYE. We anticipate that all instruments will be running continuously during the campaign, but have expressed a specific desire to prioritize the following instruments:

– Ceilometer (CEIL)
– Ka ARM Zenith Radar (KAZR)
– Sondes
– Surface meteorological instrumentation (MET)
– Microwave radiometer (MWR)
– AERI
– Eddy correlation flux measurement system (ECOR)
– Surface/sky radiation
– Doppler lidar
– Raman lidar (if possible to get it working)
– TBS ground station.

Instruments designated secondary priority include:

- Micropulse lidar (MPL)
- Aerosol observing system (AOS) CPC
- AOS cloud condensation nuclei particle counter (CCN)
- AOS nephelometer
- Total sky imager (TSI)
- Precipitation equipment, including multi-angle snowflake camera (MASC).

In addition to the routine operation of AMF3, POPEYE will include a third daily radiosonde launch. The three balloons will be launched at 0000, 0600 and 1800 UTC (1500, 0600, 1800 local time). These extra radiosondes will provide additional information on the evolution of the entire atmospheric column and contribute to the enhanced radiosonde launches to be completed under YOPP during the SOPs.

3.2 Location 2 (AAF)

During POPEYE, the ARM Aerial Facility (AAF) will operate the DataHawk2 (DH2) UAS. DataHawk operations will consist of several (6+ preferred) regular ~1-hour flights per day during daytime (i.e., 6 am to 6 pm) hours, with three flights evenly spaced around daytime radiosonde launches. These flights will include profiling continuously in a loiter circle over the site between 15 m and the maximum allowable altitude under the regulations governing ARM's operation of these systems. Under cloudy conditions, the aircraft will hold altitude as close to cloud base as possible for 15 minutes at a time in order to collect information on turbulent fluxes into the cloud base. The AAF has worked with the University of Colorado (CU) to integrate an iMet sensor package to improve measurements of temperature and humidity.

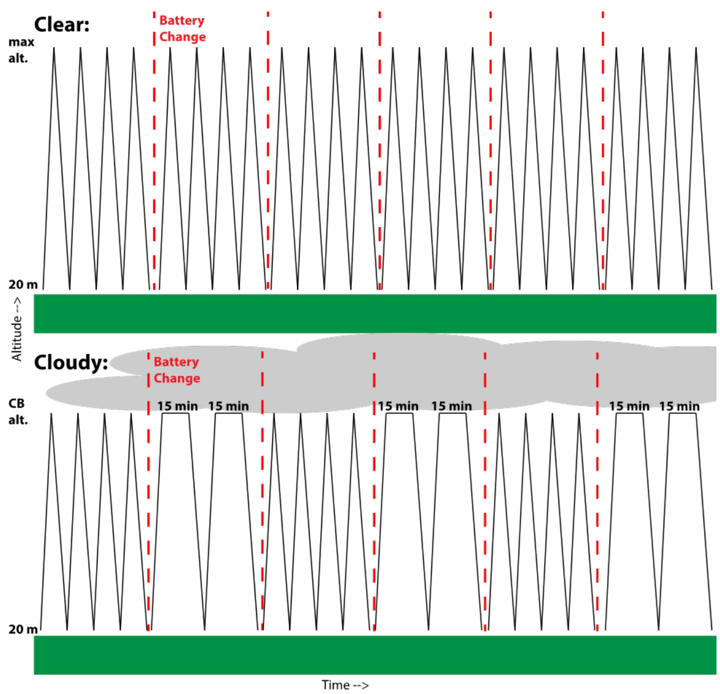

Figure 1. Diagrams of the flight pattern for the DataHawk2 during POPEYE for both clear (top) and cloudy (bottom) conditions.

3.3 Location 3 (TBS)

Tethered balloon operations will consist of operating the distributed temperature system (DTS) continuously on a daily basis, with TBS and DH2 operations occurring in alternating two-week periods. In addition to the DTS, the TBS will carry tethersondes, super-cooled liquid water content (SLWC) sensors and aerosol instrumentation (e.g., portable optical particle counter [POPS], condensation particle counter [CPC]). The TBS provides a unique opportunity to sample lower-atmospheric clouds and the associated aerosols and thermodynamic structure in situ.

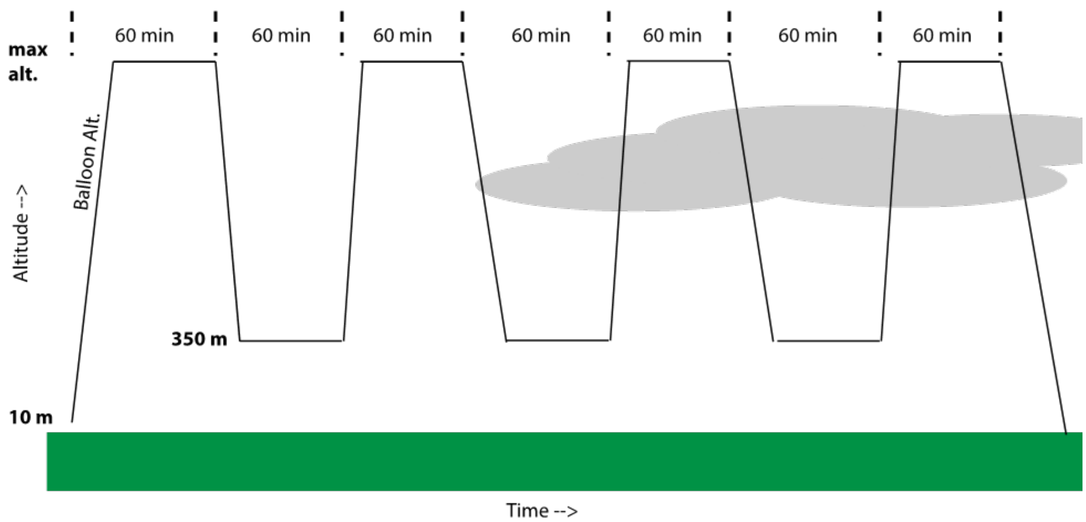

Figure 2. Diagram of the proposed TBS flight pattern for clear (left) and cloudy (right) conditions.

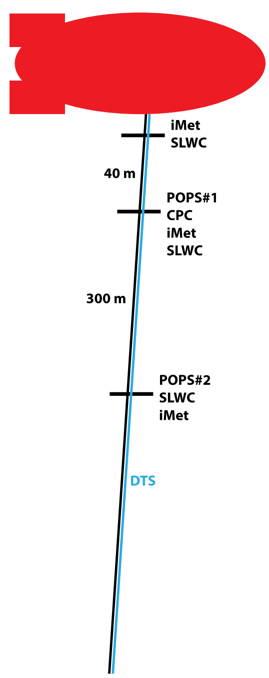

Figure 3. Proposed payload configuration for the TBS.

4.0 Project Management and Execution

POPEYE will take place between 1 July and 30 September 2018. TBS and DH2 teams will alternate in 14-day blocks to provide nearly continuous sampling over the entire three-month period. The only week that is not covered is the one between 29 August and 5 September. In addition, the AMF3 technicians will launch an extra radiosonde daily during this time frame. The PI team, consisting of Gijs de Boer, Matthew Shupe, Amy Solomon, and Janet Intrieri, plan to be engaged with the team in the field for four 1-week overlap periods. Additionally, cross-platform instrument calibration efforts will be undertaken at every transition period to help ensure that measurements from the two platforms and AMF3 instrumentation can be intercompared and used together. A detailed calibration plan is being provided to the participating entities.

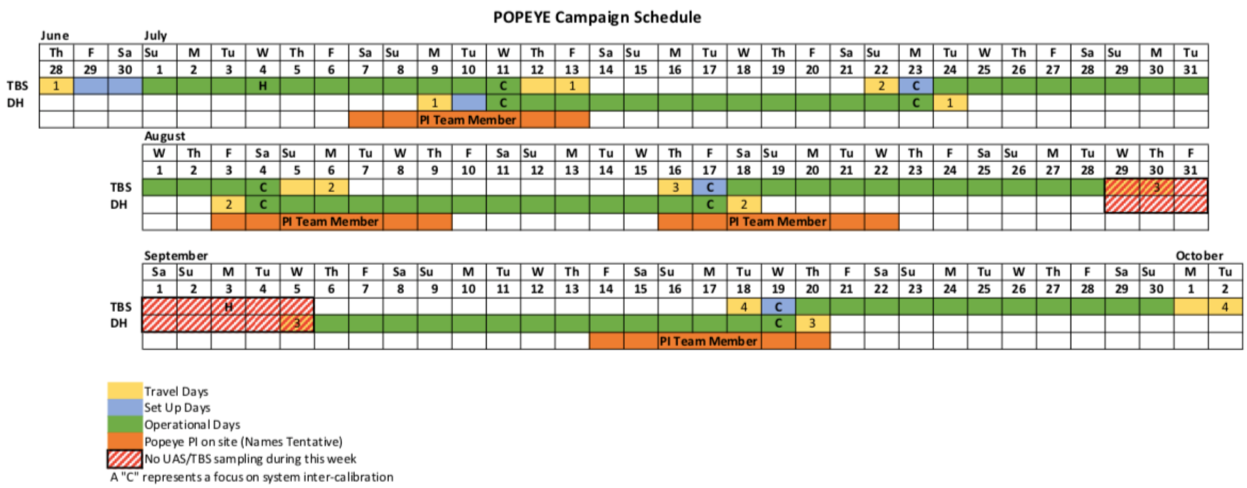

Figure 4. POPEYE operational schedule.

5.0 Relevancy to the ARM Mission

POPEYE would complement the DOE Office of Biological and Environmental Research (BER) Climate and Environmental Sciences Division (CESD) mission in several ways. Based on the CESD strategic plan, these contributions could be broken down into several different categories, with direct statements from the CESD strategic plan included *in italics*:

1. POPEYE supports several Atmospheric System Research (ASR) objectives from the CESD plan. First, it provides data sets to be used for evaluation and development of retrieval techniques, and for quantification of retrieval uncertainty, thereby "*Utilizing and extending the capabilities of the new Recovery Act instruments and ARM facility sites. To enhance characterization of cloud, aerosol, and precipitation properties ASR will prioritize and solicit targeted research to develop new analyses and data techniques suitable for the new instrumental capabilities (e.g., retrieval development, uncertainty analysis, data product collocation)*". Additionally, POPEYE measurements provide needed insight into the distribution of aerosol particles and cloud microphysical properties, complementing surface-based measurements in "*support of integrated studies of key processes driving aerosol-cloud-precipitation-radiation interactions*". Finally, POPEYE provides a unique data set that can be evaluated in the context of a much broader international effort to "*Continue investigations into dominant atmospheric processes in tropical, marine, and arctic environments*"

specifically including analysis of "*upcoming measurements from the arctic Oliktok site as well as existing and anticipated arctic campaign data*."

2. In support of the Regional and Global Climate Modeling Program, POPEYE will enhance our ability to conduct focused investigations of the Arctic, an identified climatically sensitive and vital region. Under this program, CESD is specifically looking to evaluate the Arctic to "*Analyze the complex interactions between sea ice, ice sheets, cold oceans, regional climate, and permafrost stability in the context of both high-resolution regional and global models*." This ultimately helps to inform earth system model (ESM) development.

3. Finally, POPEYE supports several ARM goals from the CESD plan. First, it connects back to "*Deployment of the third mobile facility at Oliktok, Alaska*" and "*couples it with regular deployments of small unmanned aerial vehicles (UAVs) for in situ measurements, launching a multi-year effort to provide critical cloud and aerosol properties over land, oceans, and sea ice*." The latter part of this statement essentially is what POPEYE will do (together with TBS and additional radiosondes launches). In addition, enhanced observations at Oliktok Point foster comparison with observations from Barrow, thereby helping to "*develop grid-scale products for improving model representation of Arctic atmospheric dynamics, cloud, aerosol, and precipitation processes*". Since both sites would have 4x daily radiosondes, studies on synoptic scale similarity between the two sites and the diurnal cycle of the North Slope could be completed. Finally, the direct connection with YOPP would help meet the CESD stated goal of "*developing long-term collaborations with European partners to ensure the availability and common format of critical field data needed to improve climate models*." Such collaborations will be a crucial part of YOPP due to the international nature of the Arctic and the need to consolidate a wide variety of measurements that will be obtained by the global arctic research community.

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