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POPSnet-SGP: A Pilot Aerosol Microphysics Network for Targeting Climate Model Uncertainty Interim Field Campaign Report

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Acronyms and Abbreviations

AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
BNL	Brookhaven National Laboratory
NOAA	National Oceanic and Atmospheric Administration
POPSnet	Printed Optical Particle Spectrometer Network
SGP	Southern Great Plains

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1.0 Summary

Aerosols mediate the radiative fluxes in clear and cloudy skies and dominate the uncertainty in the radiative forcing of climate. Relatively dense networks of aerosol optical depth measurements have been used to effectively constrain simulated aerosol optical properties, but model diversity of aerosol microphysical properties is much larger (Mann et al. 2014, Myhre et al. 2009). A better understanding of aerosol microphysics is essential as they are the fundamental pieces of information required to convert aerosol emissions information to radiative and cloud-nucleating properties that drive radiative effects and forcing of climate. Model representation of aerosol microphysical properties has lagged in part due to their inherently greater spatial variability, but also due to a lack of available observations. This project – the Printed Optical Particle Spectrometer Network (POPSnet)-Southern Great Plains (SGP) Pilot – launched the first spatially dense network of aerosol size distribution measurements over an area the size of a global model grid cell and demonstrated its use in providing valuable information regarding the spatial variability of aerosol microphysical properties and its drivers for improving model constraints.

POPSnet demonstrated a measurement strategy designed to minimize a major source of uncertainty associated with comparing global models with point measurements – the 'representation error' (Schutgens et al. 2017.) The representation error arises because aerosol concentrations at a single measurement location can be persistently higher or lower than the average across a large model grid cell (i.e., the measurement location is not representative of the area.) The representation error has so far been estimated by comparing high-resolution models, standing in for observations of real-world variability, with low-resolution global models with grid cells on the order of 100 km. These studies showed that time-averaged aerosol concentrations can vary by a factor of five or more across a typical grid box, and one-standard-deviation relative errors can be around 30% or more (Reddington et al. 2017, Schutgens et al. 2017.)

Estimates of the representation error show that it often exceeds the uncertainty of common aerosol in situ instruments (Reddington et al. 2017). Therefore, the extent to which measurements help to constrain model uncertainty may be limited as much by the measurement strategy as by instrument accuracy. While low-cost instruments may lack some features of conventional instruments, when deployed in such a way as to target the representation error, they are more likely to provide the specific information needed to reduce the large uncertainty range in global climate model simulations. POPSnet challenged the conventional approach of comprehensive and detailed but sparse aerosol measurement systems by adding adequate information in the spatial dimension.

Making this new measurement approach possible was the development of the Printed Optical Particle Spectrometer (POPS; Gao et al. 2016) – a lower-cost, but robust, research-grade aerosol instrument. POPS is a high-sensitivity instrument that sizes individual particles within the range of 0.14-2.5 µm based on the scattered light produced as each particle passes through a focused laser beam and segregates these signals into specified size bins. The instrument flow rate is used to calculate the particle concentration (cm^{-3}) in each size bin.

POPSnet-SGP comprises seven sites in northern Oklahoma, at the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) user facility SGP observatory, including the SGP central facility and six extended facility sites. The sites are distributed across a ~150-km x ~150-km region,

spanning the latitude range 35.86-37.15 N and longitude range 96.76-98.36 W, with altitudes between 247 and 418 m above sea level. Logistical considerations contributed to choosing ARM-SGP as the location for this pilot network, including its infrastructure and available ancillary measurements of aerosol, cloud, radiation, and atmospheric dynamics and state properties. The network is configured with two POPS mounted side by side in the shelters with custom-built infrastructure for air sampling and flow and data communications. Two instruments were deployed at each network node to quantify measurement error and to calculate the systematic error in aerosol sizing that could result from an incorrect assumption of the bulk index of refraction. The original plan was to deploy at 14 sites but after the first phase of deployment, the COVID-19 pandemic made it impossible to carry out the second phase and maintain full operations over the two-year campaign. Autonomous, nearly continuous operation of POPSnet-SGP was achieved from mid-October 2019 through mid-March, 2020. Throughout this period, five of seven sites were often operational, each of which included two POPS operating side by side. Factors that might contribute to the observed differences in aerosol distributions across a region, including local meteorology, transport, and the primary aerosol emissions, were examined with results reported in Asher et al. 2022 and summarized below.

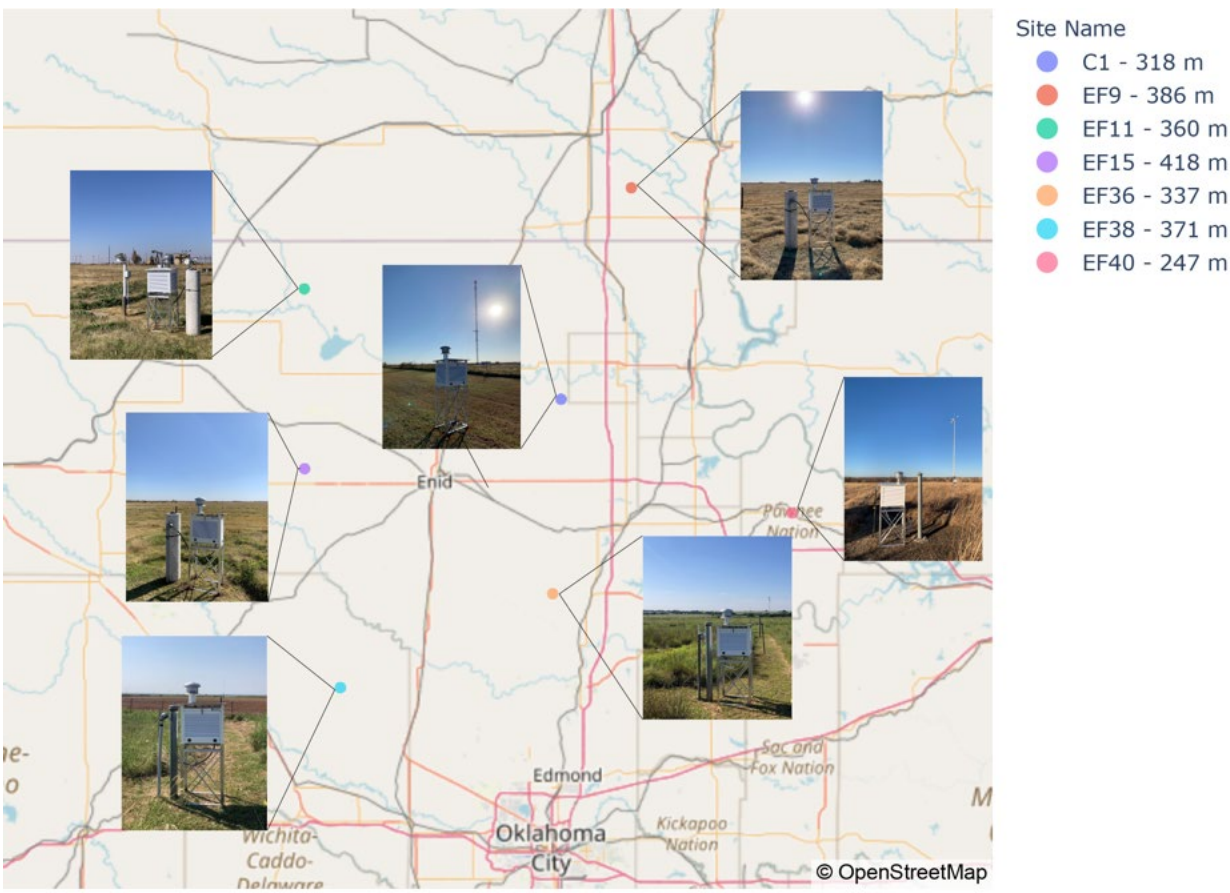

Figure 1. Map of the layout of ARM's SGP observatory, including the central facility and extended facilities used in this research.

2.0 Results

All results from POPSnet-SGP to date are presented in Asher et al. (2022) with some high-level results presented here. Our data suggest that three quarters of total aerosol concentration, aerosol surface area, and aerosol concentration > 400 nm measurement representation error distributions remained < ± 19%, < ± 15%, and < ± 28%, respectively, provided a 30-minute averaging period. Representation error decreased with increasing averaging periods (1 min – 1 day) by 30%-45% and routinely exceeded the POPS measurement error. Differences in the representation error among individual stations illustrate the importance of site selection and suggests that the central facility is well suited for large-scale regional studies. Information on the representation error in the Southern Great Plains region may establish a prior baseline for the representation error of other remote regions and could be scalable over similar large areas of the globe.

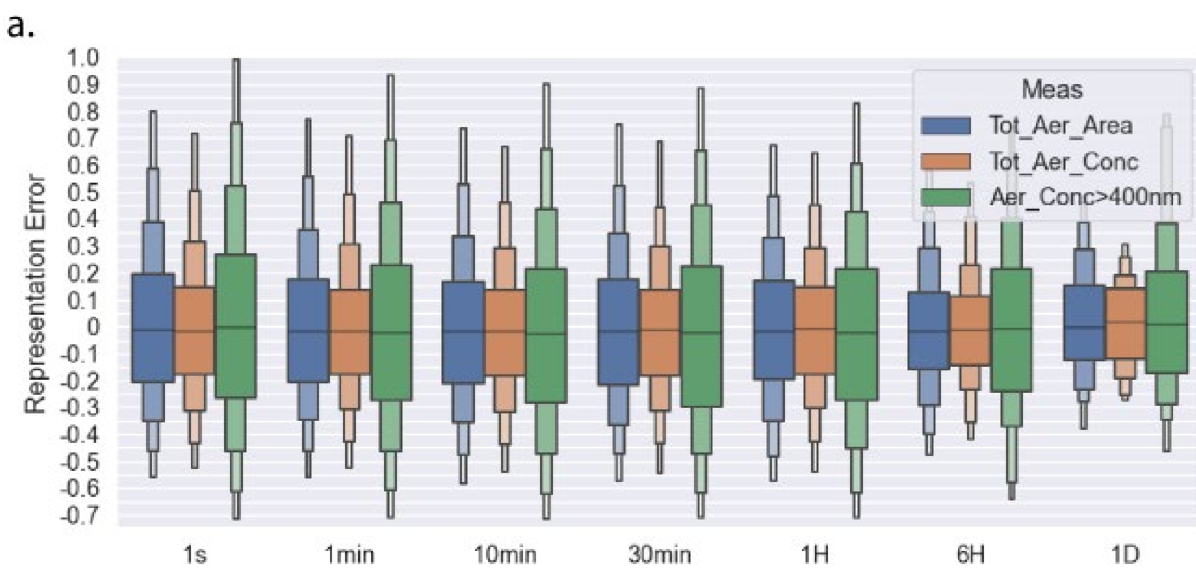

Figure 2. Representation error distribution across all stations (quantiles 0.05, 0.0625, 0.125, 0.25, 0.5, 0.75, 0.875, 0.935, 0.95) for total aerosol concentration, total aerosol concentration greater than 400 nm, and total aerosol surface area as a function of averaging period. The mean and standard deviation of representation error for total aerosol concentration, aerosol concentration with diameter >400 nm, and aerosol surface area from each station with an averaging period of 30 min.

Our measurements provide insight into transport across the SGP region, occasional localized primary aerosol emissions, and the influence of local meteorology leading to measurement representation error. Comparisons between tower-based and ground-based POPS are needed to determine if a near-surface, in situ aerosol measurement is representative of the boundary layer during the day, and confirm to what extent these become decoupled at night. We expect that the expansion of POPSnet to other, more heterogenous environments will reveal greater spatial variability in aerosol distributions with an increased likelihood of large representation errors.

ARM has emphasized the need to "develop new data products and tools to bridge observations and models" and specifically to bridge the spatio-temporal gap between observations and models. POPSnet is an observational tool designed specifically for this purpose with companion modeling tools developed by our principal investigator team. While much can be contributed by furthering the sophistication of data products derived from detailed measurements made at a single location, the observation-model spatio-temporal gap will persist without a new measurement approach. To this end, development of POPSnet into a more comprehensive and mobile capability for ARM Mobile Facility (AMF) deployment will provide the opportunity for characterization of aerosol variability and drivers in differing climate regimes.

3.0 Publications and References

3.1 Publications

An overview of the POPSnet-SGP Pilot was recently published:

Asher, E, T Thornberry, DW Fahey, A McComiskey, K Carslaw, S Grunau, K-L Chang, H Telg, P Chen, and R-S Gao. 2022. "A novel network-based approach to determining measurement representation error for model evaluation of aerosol microphysical properties." *Journal of Geophysical Research – Atmospheres* 127(3): e2021JD035485, https://doi.org/10.1029/2021JD035485

3.2 References

Gao, R-S, H Telg, RJ McLaughlin, SJ Ciciora, LA Watts, MS Richardson, JP Schwarz, AE Perring, TD Thornberry, AW Rollins, MZ Markovic, TS Bates, JE Johnson, and DW Fahey. 2016. "A Light-Weight, High-Sensitivity Particle Spectrometer for PM2.5 Aerosol Measurements." *Aerosol Science and Technology* 50(1): 88–99, https://doi.org/10.1080/02786826.2015.1131809

Mann, GW, KS Carslaw, CL Reddington, KJ Pringle, M Schulz, A Asmi, DV Spracklen, DA Ridley, MT Woodhouse, LA Lee, K Zhang, SJ Ghan, RC Easter, X Liu, P Stier, YH Lee, PJ Adams, H Tost, J Lelieveld, SE Bauer, K Tsigaridis, TPC van Noije, A Strunk, E Vignati, N Bellouin, M Dalvi, CE Johnson, T Bergman, H Kokkola, K von Salzen, F Yu, G Luo, A Petzold, J Heintzenberg, A Clarke, JA Ogren, J Gras, U Baltensperger, U Kaminski, SG Jennings, CD O'Dowd, RM Harrison, DCS Beddows, M Kulmala, Y Viisanen, V Ulevicius, N Mihalopoulos, V Zdimal, M Fiebig, H-C Hansson, E Swietlicki, and JS Henzing. 2014. "Intercomparison and Evaluation of Global Aerosol Microphysical Properties among AeroCom Models of a Range of Complexity." *Atmospheric Chemistry and Physics* 14 (9): 4679–4713, https://doi.org/10.5194/acp-14-4679-2014

Myhre, G, M Kvalevåg, G Rädel, J Cook, KP Shine, H Clark, F Karcher, K Markowicz, A Kardas, P Wolkenberg, Y Balkanski, M Ponater, P Forster, A Rap, and RR De Leon. 2009. "Intercomparison of Radiative Forcing Calculations of Stratospheric Water Vapour and Contrails." *Meteorologische Zeitschrift* 18(6): 585–596, https://doi.org/10.1127/0941-2948/2009/0411

Reddington, CL, KS Carslaw, P Stier, N Schutgens, H Coe, D Liu, J Allan, J Browse, KJ Pringle, LA Lee, M Yoshioka, JS Johnson, LA Regayre, DV Spracklen, GW Mann, A Clarke, M Hermann, S Henning, H Wex, TB Kristensen, WR Leaitch, U Pöschl, D Rose, MO Andreae, J Schmale, Y Kondo, N Oshima, JP Schwarz, A Nenes, B Anderson, GC Roberts, JR Snider, C Leck, PK Quinn, X Chi, A Ding, JL Jimenez, and Q Zhang. 2017. "The Global Aerosol Synthesis and Science Project (GASSP): Measurements and Modeling to Reduce Uncertainty." *Bulletin of the American Meteorological Society* 98(9): 1857–1877, https://doi.org/10.1175/BAMS-D-15-00317.1

Schutgens, N, S Tsyro, E Gryspeerdt, D Goto, N Weigum, M Schulz, and P Stier. 2017. "On the Spatio-Temporal Representativeness of Observations." *Atmospheric Chemistry and Physics* 17(16): 9761–9780, https://doi.org/10.5194/acp-17-9761-2017

4.0 Lessons Learned

This small ARM campaign was a pilot project intended to develop and work through challenges of deploying the first distributed and spatially dense measurement network for aerosol microphysical properties over a global climate model grid cell area. Hence, the many lessons learned were a major outcome of the deployment. These lessons are being used to update the network for an extended period and the solutions to the issues that we are currently taking are indicated here.

Humidity has caused corrosion

- New POPS are being fully conformally coated to be more impervious to corrosion.

Microblowers have failed

- Designed especially for POPSnet/long-term, boundary-layer and tropospheric operation
- Become clogged with large particles
- Filters installed in front of each microblower
- May need to be switched out every few months
- Continued POPSnet operation will have filter spares on hand to prevent microblower failure and hot-spare instruments in the case of microblower failure.

Data communications is challenging

- Long-term application for ARM requires an ARM site-specific solution
- Discussions with ARM data communications staff have informed plans for replacing current communications with MOXA computers that integrate seamlessly in ARM site networking
- We plan to order a MOXA unit and return one POPSnet node to Brookhaven National Laboratory (BNL) to integrate data communication into the network that will allow for seamless flow of the data through the ARM system.

Science served by distributed networks can be enhanced through computational frameworks that optimize deployment design for particular science applications

- New models are being developed for observing system simulation experiments targeted at SGP and planned AMF deployments, particularly in the American Southeast.

Our objective is to run POPSnet-SGP for an additional year with refurbished instruments and network updates guided by these lessons. During this time, network nodes will be modified and expanded in terms of the number of instruments employed and communications hardware that will allow for connection with the ARM data network. Once these updates are established, POPSnet can be moved to other locations to accompany AMF deployments. The principal investigator is discussing these potential activities with ARM management.

5.0 Extension Requirements

As expressed above, the team was confronted with significant challenges due to the COVID-19 global pandemic. This included the ability to deploy the original intended number of measurement nodes (14) in the network. However, we found that using half the number of measurement nodes was sufficient for this pilot effort largely focused on testing and refining the approach. The results did also provide valuable information on the spatio-temporal variability of aerosol at the ARM SGP site.

Maintaining continuous operation of the network was also a challenge due to restrictions in the ability to visit the site or even our home laboratories where replacement instruments could be prepared and sent to the site. Given that the network was newly built for this deployment, many fixes were required within the two years to maintain measurement continuity (as outlined in the Lessons Learned section). Now that we are back to our home institutions and able to travel, and we have determined the challenges and solutions to maintaining continuous operation of the network (Lessons Learned), we can deploy the second phase of the pilot to demonstrate an approximate year of continuous operations.

To prepare for this pilot extension, we have and are taking a number of steps that are in various stages of completion:

- SGP site visit by principal investigator McComiskey provided an opportunity to review the challenges and needed improvements with SGP staff (Chris Martin, Bryan Williams, Rod Marler, David Swank) from the perspective of improving regular maintenance protocols and data communications that will lead to uninterrupted operation of the network.
- Principal investigator McComiskey presented POPSnet extension and potential mentorship scenarios to ARM management, who expressed interest in a transition year to refurbish the network and collect several months of continuous data.
- NOAA has acquired 14 new POPS to deploy in the network – these will replace the existing/original instruments that are in variable states of health.
- NOAA and BNL are working together to get these new instrument conformally coated to avoid continuity issues related to corrosion.
- Plans for deploying the new instruments and reviewing maintenance protocols with ARM site staff are focused on sometime around May 2022 if this extension is approved.
- Filters for blowers and other spares are being collected to ensure quick turnaround in the case of instrument failure during the extension period.

- BNL will commit time from an ARM aerosol instrument mentor intimately familiar with POPS and size distribution measurements in general to monitor the network over the extension period.
- During this period, BNL will begin expanding the measurement capabilities of the network and transfer of data communications to hardware compatible with the ARM system.

In addition to demonstrating continuous operation of the network over an extended period, the extension will continue to provide spatially distributed data. With a longer-running set of data over an additional year, we will be working to integrate these data into models, which was difficult with the discontinuous data set from the first phase of the pilot project. The existing and newly collect (extension) data sets will be submitted to the ARM Data Center.

The measurement approach that POPSnet capacitates fills a measurement need articulated by ARM that in turn fills the knowledge gap in aerosol science described above. Fully developing and demonstrating the network during this extension period will allow for the application of this approach to future ARM deployments in differing aerosol and climate regimes that will address this knowledge gap.

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