AMERICAN
METEOROLOGICAL
SOCIETY

Bulletin of the American Meteorological Society

EARLY ONLINE RELEASE

The DOI for this manuscript is doi: 10.1175/BAMS-D-17-0175.1

The final published version of this manuscript will replace the preliminary version at the above DOI once it is available.

If you would like to cite this EOR in a separate work, please use the following full citation:

Andrews, E., P. Sheridan, J. Ogren, D. Hageman, A. Jefferson, J. Wendell, A. Alastuey, L. Alados-Arboledas, M. Bergin, M. Ealo, A. Hallar, A. Hoffer, I. Kalapov, M. Keywood, J. Kim, S. Kim, F. Kolonjari, C. Labuschagne, N. Lin, A. Macdonald, O. Mayol-Bracero, I. McCubbin, M. Pandolfi, F. Reisen, S. Sharma, J. Sherman, M. Sorribas, and J. Sun, 2018: Overview of the NOAA/ESRL Federated Aerosol Network. Bull. Amer. Meteor. Soc. doi:10.1175/BAMS-D-17-0175.1, in press.

Overview of the NOAA/ESRL Federated Aerosol Network

Elisabeth Andrews[1], Patrick J. Sheridan[2], John A. Ogren[2], Derek Hageman[1], Anne Jefferson[1], Jim Wendell[2], Andrés Alastuey[3], Lucas Alados-Arboledas[4], Michael Bergin[5], Marina Ealo[3], A. Gannet Hallar[6,7], Andras Hoffer[8], Ivo Kalapov[9], Melita Keywood[10], Jeongeun Kim[11], Sang-Woo Kim[12], Felicia Kolonjari[13], Casper Labuschagne[14], Neng-Huei Lin[15], AnneMarie Macdonald[13], Olga L. Mayol-Bracero[16], Ian B. McCubbin[7], Marco Pandolfi[3], Fabienne Reisen[10], Sangeeta Sharma[13], James P. Sherman[17], Mar Sorribas[18], Junying Sun[19]

[1]Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, CO USA

[2]Earth System Research Laboratory (ESRL), National Oceanic and Atmospheric Administration (NOAA), Boulder, CO USA

[3]Institute of Environmental Assessment and Water Research, Barcelona, Spain

[4]Andalusian Institute for Earth System Research, IISTA-CEAMA, University of Granada, Granada, Spain

[5]Department of Civil & Environmental Engineering, Duke University, Durham, NC, USA

[6]University of Utah, Department of Atmospheric Science, Salt Lake City, UT, USA

[7]Storm Peak Laboratory, Desert Research Institute, Steamboat Springs, CO, USA

[8]MTA-PE Air Chemistry Research Group, University of Pannonia, Veszprém, Hungary

[9]Institute for Nuclear Research and Nuclear Energy, Basic Environmental Observatory Moussala, Sofia, Bulgaria

[10]CSIRO Oceans and Atmosphere, Aspendale, Australia

[11]Environmental Meteorology Research Division, National Institute of Meteorological Sciences (NIMS), Seogwipo-si, Jeju-do, R. Korea

[12]School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea

[13]Environment and Climate Change Canada, Toronto, Ontario, Canada

[14]Climate Environmental Research Monitoring (CERM), South African Weather Service, Stellenbosch, South Africa

[15]Department of Atmospheric Sciences, National Central University, Taoyuan, Taiwan

[16]Department of Environmental Science, University of Puerto Rico - Rio Piedras, San Juan, Puerto Rico, USA

[17]Deptartment of Physics and Astronomy, Appalachian State University, Boone, NC, USA

[18]El Arenosillo Atmospheric Sounding Station, Atmospheric Research and Instrumentation Branch, National Institute for Aerospace Technology (INTA), Huelva, Spain

[19]State Key Laboratory of Severe Weather & Key Laboratory of Atmospheric Chemistry of CMA, Chinese Academy of Meteorological Sciences, Beijing, Peoples Republic of China

Corresponding author: Elisabeth Andrews,
Email: betsy.andrews@noaa.gov
Address: NOAA/ESRL/GMD, 325 Broadway, Boulder, CO 80305, USA
Phone: 303-497-5171

Overview of the NOAA/ESRL Federated Aerosol Network

Capsule

The cooperative nature of NOAA's Federated Aerosol Network allows for collection of consistent datasets for evaluating regionally representative aerosol climatologies, trends, and radiative forcing at 30 sites around the world.

Abstract

In order to estimate global aerosol radiative forcing, measurements of aerosol optical properties are made by the NOAA Earth System Research Laboratory's Global Monitoring Division (ESRL/GMD) and their collaborators at 30 monitoring locations around the world. Many of the sites are located in regions influenced by specific aerosol types (e.g., Asian and Saharan desert dust, Asian pollution, biomass burning, etc.). This network of monitoring stations is a shared endeavor of NOAA and many collaborating organizations, including the World Meteorological Organization Global Atmosphere Watch (WMO/GAW) Program, the U.S. Department of Energy (DOE), several U.S. and foreign universities, and foreign science organizations. The result is a long-term, cooperative program making atmospheric measurements that are directly comparable with those from all the other network stations and with shared data access. The protocols and software developed to support the program facilitate participation in GAW's atmospheric observation strategy and the sites in the NOAA/ESRL network make up a substantial subset of the GAW aerosol observations. This paper describes the history of the NOAA/ESRL Federated Aerosol Network, details about measurements and operations and some recent findings from the network measurements.

1. Introduction

Climate change is one of the most important environmental, social, economic, and political issues facing the planet today. Aerosol particles may have either a warming or cooling effect at the top-of-atmosphere, depending both on properties of the aerosol and the underlying surface (IPCC, 2013). Atmospheric aerosol particles interact with solar radiation by absorbing and scattering light. The amount of scattering and absorption is a function of particle size, composition, and shape, as well as external variables like relative humidity (RH) and wavelength of incident light. The regional influence of aerosol particles on climate and weather tends to be stronger than their global average impact, due to their relatively short atmospheric lifetimes and inhomogeneity in sources and processing. Thus, to understand the global influence of aerosol particles, it is necessary to make long-term measurements at many regionally representative sites (e.g., Laj et al., 2009; Lund Myhre and Baltensperger, 2012). Short-term aerosol campaign measurements are typically designed to study specific processes and/or events, but long-term measurements are often needed to put such data into a broader context, e.g., to assess whether field campaign measurements represent that location and season, as well as for assessing trends and variability. Such long-term measurements can take the form of ground-based remote sensing, satellite-based remote sensing, and/or ground-based in-situ sites. While the focus here is on long-term, surface in-situ sites, it is important to recognize the synergy obtained when data from multiple independent platforms are combined (e.g., Ogren, 1995; Kahn et al., 2004, 2017; Anderson et al., 2005). For example, combining surface measurements with airborne or remote sensing platforms enables the connection of ground-based aerosol properties to vertically-resolved processes. While ground-based, in-situ measurements cannot represent the properties of aerosols that are present in layers aloft, multi-year in-situ aerosol profiling measurements over two FAN sites in the US have shown that ground-based measurements of aerosol intensive properties such as single scattering albedo and scattering Ångström exponent can represent the climatology of those properties aloft under well-mixed conditions (Andrews et al., 2004; Sheridan et al., 2012).

Numerous stations around the world make long-term in-situ measurements of regionally-representative aerosol optical properties. Originally, many of these sites were operated in isolation to address specific scientific goals with sampling and data protocols designed to meet those goals, making it difficult to utilize those data in wider studies and inter-comparisons (Kulmala et al., 2011). Several recent papers note the importance of consistent operational and data processing among sites in order to improve data quality control and access across locations (e.g., Kulmala et al., 2011; Wiedensohler et al., 2012). In contrast, some sites (e.g., the original NOAA Baseline Observatories, Bodhaine, 1983) were conceived as part of a network where similarities in instruments, protocols, and a common data archive resulted in complete intra-network consistency, although extra-network comparisons were limited by differences in data collection and/or treatment. Recognition of the need for consistent measurements drives the development of protocols for instruments and data treatment (e.g., WMO, 2016).

This paper presents a description of the current NOAA Federated Aerosol Network (FAN), which evolved from the original NOAA baseline network. The two primary purposes of this paper are (1) to describe the current state of the FAN (including its member stations, the measurements common to most of the stations, and the sampling and measurement protocols) and (2) to show examples of the science that is possible with a global network of this type. A number of earlier papers (e.g., Sheridan et al., 2001; Delene and Ogren, 2002; Sherman et al., 2015) touched on some aspects of this, utilizing small subsets of the network (1 to 4 stations) but, until now, there have been no papers describing the FAN in its entirety. The paper begins with a brief history of the network, discusses the key measurements and measurement protocols made at network sites, describes the software for data acquisition and processing, and finally, presents an overview of scientific results from FAN measurements over the last 15 years.

2. History of the NOAA Federated Aerosol Network

The current network mission is to characterize the means, variability, and trends of climate-forcing properties of different types of aerosols, and to understand the factors that control these properties. In the 1970s, NOAA's Environmental Research Laboratories (ERL) Geophysical Monitoring for Climatic Change (GMCC) Program had the mission to detect changes (i.e., trends, cycles) in the long-term global aerosol background values. To do so, GMCC conducted aerosol measurements at four baseline observatories. The original NOAA Baseline Observatories (Mauna Loa, Hawaii (MLO), the South Pole (SPO), American Samoa (SMO), and Barrow, Alaska (BRW)) appear along the left-hand side of Figure 1. These sites are remote from aerosol sources and typically represent clean background air, although, occasionally, they may be impacted by long range transport (e.g., Perry et al., 1999; Stone et al., 2007).

Since the initial founding of the baseline observatory network, the scientific understanding of the properties and impacts of atmospheric aerosols has improved considerably. In response to the finding that anthropogenic aerosols create a significant perturbation in the Earth's radiative balance on regional scales (e.g., Bolin and Rodhe, 1976; Charlson et al., 1991), NOAA expanded its aerosol research program starting in 1992 to include four sites in North America: Bondville, Illinois (BND, collaboration with University of Illinois), Sable Island, Nova Scotia (WSA, collaboration with Environment and Climate Change Canada), Southern Great Plains (SGP, collaboration with US Department of Energy)) and Trinidad Head, California (THD). These site locations were chosen because they are at times impacted by anthropogenic aerosols and consequently address the need to better understand how human activity can influence the radiation balance. Although these sites are not as remote as the baseline observatories, they also are not close to major anthropogenic aerosol sources (e.g., Delene and Ogren, 2002) and typically provide measurements of regionally representative aerosol (e.g., Wang et al., 2018).

ESRL/GMD's expertise in maintaining long-term measurements of aerosol optical properties (often at remote locales) did not go unnoticed. Colleagues from around the world contacted GMD for advice on station operations and instrument maintenance and the collaborative NOAA/ESRL Federated Aerosol Network was born. The concept for and, indeed, the name of the FAN, owes much to the development of the AERONET sunphotometer network in the mid-1990s (Holben et al., 1998). The definition of a federation is groups "*that have joined together for a common purpose*" (Collins, 2018). The descriptor 'federated' is appropriate as the result is a long-term, cooperative program with shared data access making atmospheric measurements that are directly comparable with all the other FAN stations. FAN collaborators contribute scientific interest, instruments, onsite technicians, long-term station costs, and operations support while NOAA contributes software for data acquisition and processing, as well as technical expertise. It is a true partnership where both sides are learning from each other. A major advantage is that the NOAA software and protocols streamline data acquisition and processing (discussed below) so that more time can be spent on science. Since 2010, more than 50 papers using FAN network data have been published (NOAA, 2018a) and multiple graduate theses have also been submitted. FAN support has also improved data submission to the World Data Center for Aerosols (www.gaw-wdca.org), both in terms of quantity of data submitted and quality and completeness of the submitted data sets.

Since 2004, 25 sites operated by numerous collaborators have joined FAN (prior to 2004 only six sites were in the network – NOAA's four baseline observatories and 2 regional stations running NOAA instruments and supervised by NOAA scientists). Many of these new cooperative aerosol monitoring sites are situated in regions where significant aerosol forcing is anticipated, including locations in North America, Europe, and Asia. Figure 1 illustrates that, while there is reasonable global coverage, there are also some large spatial gaps (particularly in the southern hemisphere) due to finite funding resources and limited infrastructure as well as the lack of collaborators in those regions. NOAA has as major partners in these global and regional aerosol measurements the World Meteorological Organization Global Atmosphere Watch (WMO/GAW) Program, and several US and foreign universities and science agencies. Most of the collaborative stations are run under the auspices of the GAW network, thus FAN sites may be considered a substantial subset of the larger GAW surface in-situ aerosol monitoring network. (FAN data comprises approximately 1/3 of GAW's surface aerosol optical property measurements and dominates contributions of optical properties to GAW outside of Europe). Table S1 provides more detail about the sites shown in Figure 1.

3. Description of system

The basic aerosol optical property measurements made at FAN sites are spectral aerosol light scattering (total and backwards hemisphere) and light absorption. These are the critical parameters for determining aerosol direct radiative forcing. Most of the sites also measure aerosol number concentration. Depending on the station, additional aerosol and gas-phase measurements may be available. Over the years, NOAA/GMD has developed protocols and instrument infrastructure in order to make measurements of known, high quality and has written software to enable consistent processing, editing, and archiving of the data. NOAA (2018b) provides details, design drawings and photos of the system components (inlet, instruments, auxiliary control units, pumpbox, etc.), but brief descriptions of the main components are provided below.

3.1 Instruments

Light scattering by atmospheric aerosols at the FAN stations is measured using integrating nephelometers (currently, either the TSI (model 3563, TSI Inc., St Paul, MN) or the Ecotech (Aurora 3000/4000, Ecotech, Melbourne, Australia) nephelometer). Both instruments measure total and hemispheric aerosol back-scattering coefficients at three visible wavelengths, enabling calculation of spectral aerosol properties and various proxies describing the angular distribution of light scattering (e.g., Andrews et al., 2006). Table S1 describes the scattering and absorption instruments at each site. Table S2 in the supplemental materials gives further details (e.g., wavelengths) for the various instruments.

Aerosol light absorption is measured at FAN stations using a variety of filter-based absorption instruments. Currently, the primary light absorption instruments are the ESRL/GMD-developed three-wavelength Continuous Light Absorption Photometer (CLAP, Ogren et al., 2017) and the single-wavelength Multi-Angle Absorption Photometer (MAAP, Thermo Fisher Scientific, Franklin, MA). Many sites are also operating 7-wavelength aethalometers (Magee Scientific, Berkeley, CA) to take advantage of that instrument's broad spectral range. Previously, FAN sites used single- and multi-wavelength Particle Soot Absorption Photometers (PSAP, Radiance Research Inc., Seattle, WA) and/or broadband aethalometers.

While the instruments across the FAN are not identical, laboratory studies suggest they make comparable measurements. Intercomparisons of TSI and Ecotech nephelometers show excellent reproducibility for total scattering although the differences are slightly larger for backscattering (Mueller et al., 2011b). Mueller et al. (2011a) find good between PSAP and MAAP measurements of aerosol light absorption for a 2007 intercomparison study although less agreement existed for an earlier (2005) data set. Mueller et al (2011a) also identify a fairly wide range of variability in PSAPs, but show much of the variability was due to spot size variations and flow rate issues. The PSAPs and CLAPs in the FAN are corrected for spot size and operated at a consistent flow rate (face velocity of 0.8 m/s) to minimize these issues. Ogren et al. (2017) demonstrate excellent agreement between long-term measurements with PSAPs and CLAPs at multiple sites in the FAN. Sherman et al. (2015) present measurement uncertainties for scattering and absorption measurements as well as for calculated parameters such as single scattering albedo and Ångström exponent.

Aerosol number concentration is another common measurement at FAN sites (Table S3). The most commonly used instruments for this parameter are butanol-based particle counters. Many

FAN sites operate multiple particle counters in tandem which can provide some minimal information on aerosol size distribution because different models have different lower size cuts. Some sites also operate instruments to measure aerosol size distributions (see Table S3).

3.2 Infrastructure and Protocols

The FAN is a subset of the WMO Global Atmosphere Watch, and consequently follows the GAW aerosol guidelines and standard operating procedures (WMO, 2011; 2016). The WMO World Calibration Center for Aerosol Physics (WCCAP, 2018) organizes instrument training and evaluation workshops and performs occasional site audits that are designed to ensure consistency across the GAW network. The role of FAN, in this context, is to provide advice and tools that make it easier for stations operators to implement the recommended procedures for GAW stations.

The FAN standard aerosol inlet configuration (NOAA, 2018c) is slightly anisokinetic (i.e., Reynolds number in the range 4500-7000). The resulting turbulent conditions limit losses of super micrometer particles (Wilcox, 1956). Sampling line sizes, materials, pickoffs, and flow rates are optimized to promote maximum passing efficiency for particles that are most important to radiative forcing (i.e., particles with diameters between 0.1 and 10 μm). Because the focus is primarily on optically important aerosol, bends in tubing and obstructions upstream of instruments are minimized to limit particle losses due to impaction. Passing efficiencies for super-micron particles are 99% and 50% for 1-2 and 7-11 μm aerodynamic diameter particles, respectively. Different inlet designs and/or instruments should be used for aerosol diameters above this size range. The inlet is not optimized for ultrafine aerosol, however inlet passing efficiency calculations suggest a 99% and 50% passing efficiency for 0.1 and 0.002-0.004 μm aerodynamic diameter particles, respectively. Figure S1 in supplemental materials shows the aerosol inlet passing efficiency for several stations. Some collaborators have designed their own inlet system (see Table S3). The GAW report 227 (WMO, 2016) includes guidelines for inlet systems, including criteria and equations used to design them. GAW and FAN offer assistance to station operators to design inlet systems and calculate losses, but every site is different (e.g., surrounding terrain and vegetation, fog frequency) meaning a common design is not practical or even desirable.

The network goal is to make aerosol measurements at low relative humidity (RH<40%) which minimizes the confounding effects of aerosol amount and hygroscopicity on the optical properties, facilitating comparison of aerosol properties among FAN sites. This objective is consistent with the wider GAW sampling protocol (WMO, 2016). To achieve low RH, two approaches have been used. The first involves gentle heating (to a maximum of 40º C) of the sample lines and insulation of the sample lines downstream of the heater. Power is only applied to the heater when the sample humidity is above the desired value. The second approach is to dilute the air stream with dry, filtered air generated by a compressor system. The dilution approach is typically used at warm marine sites in the network. The amount of dilution air is measured and corrections to the measurements are applied automatically during data processing.

In order to fully characterize the sampling system, temperature, RH, flow, and pressure are monitored at several points along the sample line. Monitoring temperature and RH in several places allows determination of whether sample dewpoint temperature is maintained as the air moves through the system. Discrepancies in system dewpoint temperature can indicate a leak in the system (or, possibly, a poorly calibrated sensor). Pressure and flow measurements provide diagnostics to determine whether sample air is flowing through the system as designed. Additionally, both analog and digital flow and pressure measurements are implemented. The analog measurements (e.g., rotameters, pressure gauges, etc.) can be assessed at a glance by an on-site operator. The digital measurements are also available to the on-site operator via the data acquisition interface, but are primarily intended for someone who is remotely evaluating the data.

Many FAN sites make aerosol light scattering and absorption coefficient measurements at two size cuts (aerodynamic particle diameter <1 and <10 μm (PM1 and PM10)). ESRL/GMD has designed an 'impactor box' to smoothly integrate size cut switching into system operations. All sample air flows through a 10 μm multi-jet Berner impactor (Hillamo and Kauppinen, 1991 and references therein) prior to being sampled by instruments. On a time base interval ranging from 5 min to 30 min, depending on the site, control software closes an automated ball valve, forcing the sample flow through a 1 μm Berner impactor. A mass flow controller is used to control flow through the impactors in order to ensure the desired size cut. The impactor box also contains solenoid valves that enable the instruments to be bypassed at certain times (e.g., during impactor cleaning).

The system requires only minor intervention from on-site technicians. Technician tasks include nephelometer calibration gas checks (performed with CO2 and filtered air) to verify instrument calibration (Anderson and Ogren, 1998); impactor cleaning; filter changes for the light absorption instruments; and replenishing the operating fluid for number concentration instruments. The frequency of these tasks depends on the site. Most sites perform nephelometer calibration checks and impactor servicing on a weekly to monthly basis, while filter changes and operating fluid replenishment tend to be more frequent. Figure S2 provides an example of nephelometer calibration checks for FAN sites with at least 5 years of data. Annually, or whenever problems are suspected, FAN protocols recommend calibration of system sensors (T, P, RH, flow), cleaning of instruments and sample lines, and overnight filtered air tests on scattering and absorption instruments.

It should be noted that there is currently no calibration standard for filter-based absorption measurements (that is an area of active research, e.g., EMPIRBlackCarbon (2018)) but the flows for the absorption instruments are calibrated annually. NOAA/GMD does not utilize a calibration system for particle counters, however, two particle counters are maintained as reference standards, one of which was tested at the WCCAP for connecting the FAN measurements with the wider GAW network. Field CPCs are periodically tested against these lab reference CPCs. The CPC flows are also checked on a regular basis. Instrument intercomparisons are a major tool in the in-situ aerosol community for ensuring comparable measurements, due to the lack of calibration standards. Additionally, instrument noise evaluations are performed annually for scattering, absorption and number concentration instruments; these evaluations consist of having the instruments measure filtered air for a 12-24 h period.

3.3 Software

ESRL/GMD has developed custom software (called CPD3) for acquisition, processing, editing and archiving of data from aerosol instruments that are used in the FAN. More information about the software is available in supplemental materials but some key aspects are highlighted here. An earlier version of the ESRL/GMD software (CPD2) is also used in the CATCOS aerosol network (Capacity **B**uilding and Twinning for Climate Observing Systems, PSI (2018)). The same software suite is used for both field acquisition computers and offsite data processing and analysis. Scientists and technicians responsible for the data use another copy of CPD3 on their desktop or laptop computers to review the data for quality and completeness and flag or remove contaminated or invalid data. The CPD3 system supports direct submission of both near real-time (raw data) and annual (QC-reviewed) data to the WMO World Data Center for Aerosols.

CPD3 is highly configurable, making it simple to add or remove instruments at the field site and to change data logging parameters**.** A list of instruments that can be logged with CPD3 is available from NOAA (2018d). Because all instruments are logged on the same computer using the time server synched computer timestamp, the timestamp for every instrument is the same. Having all the instruments and infrastructure tied together enables the system to operate holistically. For example, if high particle concentrations and/or wind direction indicate local contamination can flagged automatically (e.g., Sheridan et al., 2016). Similarly, chemical filters can be automatically bypassed to avoid sampling contaminated air while other measurements are flagged (Quinn et al., 2002).

During data review, the ability to inspect multiple data streams simultaneously in a graphical interface helps both with identifying events and troubleshooting system failures. CPD3 includes a time-stamped message log enabling the data to be directly related to operator actions and observations both on the station computer and after the fact during quality control (QC) data inspection and editing. CPD3 provides tools for editing and applying standard corrections (e.g., standard temperature and pressure corrections, the truncation correction for the nephelometer (Anderson and Ogren 1998), various schemes for correcting filter-based absorption measurements (e.g., Bond et al., 1999), etc. The end result of the integrated software developed at ESRL/GMD is a self-consistent data archive standardized across all stations using the software. Final data from the NOAA/ESRL FAN are available from the WDCA (NILU, 2018) for most stations and from the PIs in all cases.

4. FAN science

While the FAN methodology is useful for a single station, its real strength lies in creating measurement consistency amongst multiple stations. Science questions that can be addressed with this data set include:

- What are the range and variability (on multiple time scales) of aerosol optical properties observed at FAN sites?
- How do long-term trends in aerosol properties compare across the globe?

By combining FAN data with external data sets, additional questions can be explored:

- Can similarities and differences among sites be related to aerosol types, sources, or processes?
- How well do global models and aerosol parameterizations in models capture aerosol properties across a range of sites?

- How consistent are the in-situ aerosol properties measured at FAN sites with remote-sensing measurements from ground- and satellite-based instruments, and how do the consistencies and inconsistencies inform interpretation of the results from all three approaches?

Figure 2 illustrates that the FAN sites cover a wide range of aerosol properties. Aerosol loading (e.g., scattering and absorption) spans nearly four orders of magnitude. While scattering at the sites is shown in monotonically increasing order, other aerosol parameters (e.g., single-scattering albedo and scattering Ångström exponent, see Table 1) vary as a function of the nature of the particles (e.g., size, composition) rather than aerosol amount. For example, the clean marine sites (Cape Grim, Australia (CGO), Cape Point, South Africa (CPT), American Samoa (SMO), Trinidad Head, CA (THD) and Cape San Juan, PR (CPR)) exhibit low scattering Ångström exponent (SAE) values indicative of large sea salt aerosol, while the low SAE at Mount Waliguan, China (WLG) can be attributed to large dust particles. Median single-scattering albedo (SSA) values are around 0.92 at most sites, although the clean marine sites exhibit higher SSA values due to predominantly white sea salt aerosol. In contrast, UGR exhibits significantly lower SSA relative to the other sites in the FAN network – the site is strongly impacted by diesel-based traffic and local biomass burning (Titos et al., 2017). The standardized FAN sampling and data processing protocols help ensure that the reported differences between stations are real and not related to operational inconsistencies. Table S1 in the supplemental materials provides more information about the stations and measurement data depicted in Figure 2. Figure S3 in supplemental materials shows the same data depicted in Figure 2 in separate sets of panes with aerosol scattering coefficient ordered by (a) elevation, (b) latitude and (c) longitude.

While Figure 2 shows annual climatological values for all sites in the network, more detailed climatologies can be evaluated as well. Figure 3 shows climatological patterns of aerosol light scattering at Bondville, IL as a function of year, month and day of year. Figure 3a shows that there has been a decrease in aerosol light scattering at Bondville since the start of measurements in the mid-1990s and that this decrease appears to have impacted scattering during all months at the site. This result is consistent with other literature documenting decreases in aerosol loading over most of the continental U.S. (e.g., Collaud Coen et al., 2013). Although aerosol amounts have decreased over the last two decades, the general picture of higher scattering during the summer remains true. Figure 3b depicts how the diurnal cycle varies with time of year. In the summer, the scattering is high throughout the day, while at other times of year the diurnal cycle is much more pronounced (similar to the observations of Sherman et al. (2015)). The diurnal minimum occurs in the early afternoon, most likely due to an increase in boundary layer height.

Detailed multi-site climatologies, including data from FAN observatories, based on location (e.g., mountain sites (Andrews et al., 2011); North American sites (e.g., Sherman et al., 2015; Delene and Ogren, 2002); and Arctic sites (Schmeisser et al., 2018)) have been published. Sites in the FAN are often members of other networks (e.g., ACTRIS, 2018; IASOA, 2018) and are included in reports on their climatologies as well (e.g., Uttal et al., 2016; Zanatta et al., 2016; Pandolfi et al., 2018). Additionally, with multiple sites one can look at the co-variability of different aerosol properties and start to identify relationships as a function of site and aerosol type (e.g., Delene and Ogren, 2002; Andrews et al., 2011; Sherman et al., 2015; Schmeisser et al., 2017*)*. Trend studies have also used data from multiple FAN sites as the focus of their investigation (e.g., Asmi et al., 2013; Collaud Coen et al., 2013; Sherman et al., 2015) to explore changes in aerosol properties as a function of location.

An additional advantage of the unified FAN data set is that it can be used to assess and improve global models. Multiple studies use FAN number concentration data to evaluate various parameterizations of aerosol nucleation (e.g., Spracklen et al., 2010; Matsui et al., 2013; Mann et al., 2014; Yu et al., 2014). Skeie et al. (2011) evaluated how well the Oslo CTM2 model simulated absorbing aerosol in terms of loading and seasonality at multiple FAN stations. There are several modeling studies using Arctic sites FAN data. For example, Sharma et al. (2013) explored the sensitivity of absorbing aerosol to wet and dry deposition, while Eckhardt et al. (2015) used Arctic surface measurements to evaluate simulated model climatologies. Currently, the FAN data are being utilized to evaluate AEROCOM (Kinne et al., 2006) global model simulations of surface aerosol scattering and absorption coefficients (Andrews et al., in preparation, 2018).

While the FAN data consistency allows for collective science using data from multiple sites, the unique locations and interests of scientists involved with each site have also resulted in many findings. For example, there have been both climatological and transport event-based studies focused on aerosol types observed at individual sites (e.g., Lim et al., 2012; Hallar et al., 2015; Sorribas et al., 2015; 2017; Denjean et al., 2016; Rivera et al., 2017; Kassianov et al., 2017). FAN measurements have been used to provide context for field campaigns (e.g., Brock et al., 2011; Bravo-Aranda et al., 2015; Denjean et al., 2016), instrument comparisons (e.g., Sharma and Barnes, 2016; Backman et al., 2017; Sinha et al., 2017; Sharma et al., 2017); remote sensing validation (e.g., Pahlow et al., 2006; Di Pierro et al., 2013; Shinozuka et al., 2015)); aerosol direct radiative forcing sensitivities and uncertainties (e.g. Sherman and McComiskey, 2018), and many other scientific efforts.

Uniting observatories under the umbrella of the Federated Aerosol Network provides the opportunity to both train and learn from a diverse group of US and international partners. The federated nature of the network enables scientists to pursue their own interests while participating in a wider goal, making the network greater than sum of its individual parts. In the process of increasing understanding of the range and variability in aerosol radiative properties, the FAN strengthens scientific ties across the globe, fostering collaborations and the exchange of knowledge. In the FAN's next 25 years, the objective is to maintain current collaborations and to establish new ones to expand the network, particularly in under-sampled regions. The FAN will continue to improve measurements, software and protocols in order to be able to address new questions as they arise. For example, in the future, a complementary network comprised of new, low-cost sensors could be developed or even used to expand the FAN or other networks pending guidance from WMO/GAW (e.g., WMO, 2018).

5. Conclusions

The FAN is a long-term, cooperative program enabling diverse sites with a wide range of aerosol types to make measurements that are directly comparable with other network stations. This facilitates the exploration of science questions at local, regional, and global scales and makes the network measurements especially useful for global model evaluation. There is a need to expand such measurements to locations that have large impacts by aerosols but little current representation in measurement databases, but of course many factors (e.g., funding) will determine whether this really takes place. The growth and scope of NOAA's collaborative network can be a model for new and existing networks which seek to expand coverage in a collaborative fashion.

Acknowledgements

The writing of this manuscript was supported by NOAA Climate Program Office's Atmospheric Chemistry, Carbon Cycle and Climate (AC4) program. The FAN network would not be possible without the interest and support of our collaborators and their students and/or technicians who maintain the stations and instruments, and keep the data flowing from their observatories.

References

ACTRIS, 2018: Research Infrastructure for the observation of Aerosol, Clouds, and Trace gases. Accessed 21 May 2018, https://www.actris.eu/.

Anderson, T.L., and Coauthors, 2005: An “A-Train” Strategy for Quantifying Direct Climate Forcing by Anthropogenic Aerosols. *Bull. Amer. Meteor. Soc.*, **86**, 1795-1809, https://doi.org/10.1175/BAMS-86-12-1795.

Anderson, T.L. and Ogren, J.A., 1998: Determining aerosol radiative properties using the TSI 3563 integrating nephelometer, *Aerosol Sci. Tech.*, **29**, 57-69, doi:10.1080/02786829808965551.

Andrews, E., and Coauthors, 2018: Comparison of aerosol optical property climatology from in-situ observations and global climate model simulations, in preparation.

Andrews, E., and Coauthors, 2011: Climatology of aerosol radiative properties in the free troposphere, *Atmos. Res.*, **102**, 365-393, https://doi.org/10.1016/j.atmosres.2011.08.017.

Andrews, E., and Coauthors, 2006: Comparison of methods for deriving aerosol asymmetry parameter, *J. Geophys. Res.*, **111**, doi:10.1029/2004JD005734.

Andrews, E., Sheridan, P. J., Ogren, J. A., and Ferrare, R., 2004: In situ aerosol profiles over the Southern Great Plains cloud and radiation testbed site: 1. Aerosol optical properties, *J. Geophys. Res.*, 109, D06208, doi:10.1029/2003JD004025.

Asmi, A., and Coauthors, 2013: Aerosol decadal trends – Part 2: In-situ aerosol particle number concentrations at GAW and ACTRIS stations, *Atmos. Chem. Phys.*, **13**, 895-916, https://doi.org/10.5194/acp-13-895-2013.

Backman, J. and Coauthors, 2016: On Aethalometer measurement uncertainties and multiple scattering enhancement in the Arctic, Atmos. Meas. Tech., accepted, https://doi.org/10.5194/amt-2016-294.

Bodhaine, B. A., 1983: Aerosol measurements at four background sites, *J. Geophys. Res.*, **88**, 10753–10768, doi:10.1029/JC088iC15p10753.

Bolin, B. and Charlson, R.J., 1976: On the role of the tropospheric sulfur cycle in the shortwave radiative climate of the Earth, *Ambio*, **3**, 47-54.

Bond, T. C., Anderson, T. L., and Campbell, D., 1999: Calibration and intercomparison of filter-based measurements of visible light absorption by aerosols, *Aerosol Sci. Technol*., **30**, 582–600, doi:10.1080/027868299304435.

Bravo-Aranda, J.A. and Coauthors, 2015: Study of mineral dust entrainment in the planetary boundary layer by lidar depolarisation technique, *Tellus B,* **67**, 26180, doi: 10.3402/tellusb.v67.26180.

Brock, C.A. and Coauthors, 2011: Characteristics, sources, and transport of aerosols measured in spring 2008 during the aerosol, radiation, and cloud processes affecting Arctic Climate (ARCPAC) Project, *Atmos. Chem. Phys.*, **11**, 2423-2453, https://doi.org/10.5194/acp-11-2423-2011.

Charlson, R.J., Langner, J., Rodhe, H., Leovy, C.B., and Warren, S.G., 1991: Perturbation of the northern hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols, *Tellus*, **43AB**, 152-163, doi:10.1034/j.1600-0870.1991.00013.x.

Collaud Coen, M., and Coauthors, 2013: Aerosol decadal trends – Part 1: In-situ optical measurements at GAW and IMPROVE stations, *Atmos. Chem. Phys.*, **13**, 869-894, https://doi.org/10.5194/acp-13-869-2013.

Collins., 2018: Definition of 'federated'. Accessed 21 May 2018, https://www.collinsdictionary.com/us/dictionary/english/federated

Delene, D. J. and Ogren, J. A., 2002: Variability of aerosol optical properties at four North American surface monitoring sites, *J. Atmos. Sci.*, **59**, 1135–1150, doi:10.1175/1520-0469(2002)059<1135:VOAOPA>2.0.CO;2.

Denjean, C. and Coauthors, 2016: Size distribution and optical properties of African mineral dust after intercontinental transport, *J. Geophys. Res.*, **121**, 7117-7138, doi:10.1002/2016JD024783.

Di Pierro, M., Jaegle, L., Eloranta, E.W., Sharma, S., 2013: Spatial and seasonal distribution of Arctic aerosols observed by the CALIOP satellite instrument (2006–2012), *Atmos. Chem. Phys.*, **13**, 13, 7075-7095, https://doi.org/10.5194/acp-13-7075-2013.

Eckhardt, S. and Coauthors, 2015: Current model capabilities for simulating black carbon and sulfate concentrations in the Arctic atmosphere: a multi-model evaluation using a comprehensive measurement data set, *Atmos. Chem, Phys*., **15**, 9413–9433, doi:10.5194/acp-15-9413-2015.

EMPIRBlackCarbon, 2018: Black Carbon Metrology for light absorption by atmospheric aerosols. Accessed 21 May 2018, http://www.empirblackcarbon.com.

Hallar, A.G., Petersen, R., Andrews, E., Michalsky, J., McCubbin, I., Ogren, J.A., 2015: Contributions of dust and biomass-burning to aerosols at a Colorado mountain-top site, *Atmos. Chem. Phys.*, **15**, 13665-13679, https://doi.org/10.5194/acp-15-13665-2015.

Hillamo, R.E. and Kauppinen, E.I, 1991: On the performance of the Berner low pressure impactor, *Aerosol Sci. Technol.*, **14**, 33-47, doi: 10.1080/02786829108959469.

Holben, B.N. and Coauthors, 1998: AERONET - A federated instrument network and data archive for aerosol characterization. *Remote Sensing of Environment*, **66**, 1-16, https://doi.org/10.1016/S0034-4257(98)00031-5.

IASOA, 2018: International Arctic Systems for Observing the Atmosphere. Accessed 21 May 2018, https://www.esrl.noaa.gov/psd/iasoa/.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

Kahn, R.A. and Coauthors, 2004: Aerosol data sources and their roles within PARAGON, *Bull. Amer. Meteor. Soc.*, **85**, 1155-1122, https://doi.org/10.1175/BAMS-85-10-1511.

Kahn, R.A. and Coauthors, 2017: SAM-CAAM: A Concept for Acquiring Systematic Aircraft Measurements to Characterize Aerosol Air Masses, Bull. Amer. Meteor. Soc, **98**, 2215-2228, https://doi.org/10.1175/BAMS-D-16-0003.1.

Kassianov, E. and Coauthors, 2017: Large Contribution of Coarse Mode to Aerosol Microphysical and Optical Properties: Evidence from Ground-Based Observations of a Transpacific Dust Outbreak at a High-Elevation North American Site, *J. Atmos. Sci.*, **74**, 1431-1443, https://doi.org/10.1175/JAS-D-16-0256.1.

Kinne, S., and Coauthors, 2006: An AeroCom initial assessment – optical properties in aerosol component modules of global models, *Atmos. Chem. Phys.*, **6**, 1815–1834, doi:10.5194/acp-6-1815-2006.

Kulmala M., and Coauthors, 2011: General overview: European Integrated project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI) – integrating aerosol research from nano to global scales, *Atmos. Chem. Phys.*, **11**, 13061–13143, https://doi.org/10.5194/acp-11-13061-2011.

Laj, P., and Coauthors, 2009: Measuring atmospheric composition change, *Atmos. Environ*., **43**, 5351-5414, doi:10.1016/j.atmosenv.2009.08.020.

Lim, S., Lee, M., Lee, G., Kim, S., Kang, K., 2012: Ionic and carbonaceous compositions of PM10, PM2.5 and PM1.0 at Gosan ABC Superstation and their ratios as source signature," Atmos. Chem. Phys., 12, 2007-2024, https://doi.org/10.5194/acp-12-2007-2012.

Lund Myhre, C. and Baltensperger, U., 2012: Recommendations for a Composite Surface-Based Aerosol Network, WMO/GAW Report 207, World Meteorological Organization, Geneva, http://library.wmo.int/pmb_ged/gaw_207.pdf.

Mann, G.W. and Coauthors, 2014: Intercomparison and evaluation of global aerosol microphysical properties among AeroCom models of a range of complexity, *Atmos. Chem. Phys.*, **14**, 4679–4713, doi:10.5194/acp-14-4679-2014.

Matsui, H. and Coauthors, 2013: Spatial and temporal variations of new particle formation in East Asia using an NPF-explicit WRF-chem model: North-south contrast in new particle formation frequency, *J. Geophys. Res.*, **118**, 11647–11663, doi:10.1002/jgrd.50821.

Mueller, T. and Coauthors, 2011a: Characterization and intercomparison of aerosol absorption photometers: result of two intercomparison workshops, *Atmos. Meas. Tech.*, 4, 245-268, doi:10.5194/amt-4-245-2011.

Mueller, T., Laborde, M., Kassell, G., and Wiedensohler, A., 2011b: Design and performance of a three-wavelength LED-based total scatter and backscatter integrating nephelometer, *Atmos. Meas. Tech.*, 4, 1291-1303, doi:10.5194/amt-4-1291-2011.

NILU, 2018: EMEP: Hosting the GAW WDCA, Accessed 21 May 2018, http://ebas.nilu.no/.

NOAA, 2018a: Network publications. Accessed 21 May 2018, ftp://aftp.cmdl.noaa.gov/aerosol/doc/newsletter/publications.html.

NOAA, 2018b: ESRL/GMD Aerosol Measurements. Accessed 21 May 2018, https://www.esrl.noaa.gov/gmd/aero/instrumentation/instrum.html.

NOAA, 2018c: Aerosol System Inlet. Accessed 21 May 2018, https://www.esrl.noaa.gov/gmd/aero/instrumentation/inlet_system.html.

NOAA, 2018d: CPD3 loggable instruments. Accessed 21 May 2018, https://www.esrl.noaa.gov/gmd/instrumentation/cpd_inst.html

Ogren, J.A., 1995: A systematic approach to in-situ observation of aerosol properties, In: *Aerosol Forcing of Climate*, eds. R. Charlson and J. Heintzenberg, John Wiley & Sons, Ltd., 215-226.

Ogren, J.A., Wendell, J., Andrews, E., and Sheridan, P., 2017: Continuous light absorption photometer for long-term studies, *Atmos. Meas. Tech.*, **10**, 4805-4818, https://doi.org/10.5194/amt-10-4805-201.

Pahlow, M. and Coauthors, 2006: Comparison between lidar and nephelometer measurements of aerosol hygroscopicity at the Southern Great Plains Atmospheric Radiation Measurement site, *J. Geophys. Res.*, **111**, doi:10.1029/2004JD005646.

Pandolfi, M. and Coauthors, 2018: A European aerosol phenomenology-6: Scattering properties of atmospheric aerosol particles from 28 ACTRIS sites, *Atmos. Chem. Phys.*, 18, 7877-7911, https://doi.org/10.5194/acp-18-7877-2018.

Perry, K.D., Cahill, T.A., Schnell, R.C., and Harris, J.M., 1999: Long-range transport of anthropogenic aerosols to the National Oceanic and Atmospheric Administration baseline station at Mauna Loa Observatory, Hawaii, *J. Geophys. Res.*, **104**, 18521-18533, doi:10.1029/1998JD100083.

PSI, 2018: CATCOS Aerosol Measurements. Accessed 21 May 2018, https://www.psi.ch/catcos/.

Quinn P. K., Miller, T. L., Bates, T. S., Ogren, J. A., Andrews, E., and Shaw, G. E., 2002: A 3-year record of simultaneously measured aerosol chemical and optical properties at Barrow, Alaska, *J. Geophys. Res.*, **107**, doi:10.1029/2001JD001248.

Rivera, H., Ogren, J.A., Andrews, E., Mayol-Bracero, O.L., 2017: Variations in the physicochemical and optical properties of natural aerosols in Puerto Rico – Implications for climate, *Atmos. Chem. Phys. Disc.*, in review, https://doi.org/10.5194/acp-2017-703.

Schmeisser, L., and Coauthors, 2017: Classifying aerosol type using in-situ surface spectral aerosol optical properties, *Atmos. Chem. Phys.*, **17**, 12097-12120, https://doi.org/10.5194/acp-17-12097-2017.

Schmeisser, L., and Coauthors, 2018: Seasonality of aerosol optical properties in the Arctic, *Atmos. Chem. Phys. Disc*, in review, https://www.atmos-chem-phys-discuss.net/acp-2017-1117..

Sharma, N.C.P., Barnes, J.E., 2016: Boundary layer characteristics over a high altitude station, Mauna Loa Observatory, *Aerosol Air Qual. Res*., **16**, 729-737, doi:10.4209/aaqr.2015.05.0347.

Sharma, S., and Coauthors, 2017: An evaluation of three methods for measuring black carbon at Alert, Canada, *Atmos. Chem. Phys. Discuss.*, **17**, https://doi.org/10.5194/acp-2017-339, in review.

Sharma, S., Ishizawa, M, Chan, D., Lavoué, D., Andrews, E., Eleftheriadis, K and Maksyutov, S., 2013: 16-year simulation of Arctic black carbon: transport, source contribution, and sensitivity analysis on deposition, *J. Geophys. Res.*, **118**, doi:10.1029/2012JD017774.

Sheridan, P.J., Delene, D.J., and Ogren, J.A., 2001: Four years of continuous surface aerosol measurements from the Department of Energy's Atmospheric Radiation Measurement Program Southern Great Plains Cloud and Radiation Testbed site, *J. Geophys. Res.* **106**, 20735-20747, doi:10.1029/2001JD000785.

Sheridan, P.J., Andrews, E., Ogren, J.A., Tackett, J., Winker, D.M., 2012: Vertical profiles of aerosol optical properties over central Illinois and comparison with surface and satellite measurements," Atmos. Chem. Phys., 12, 11695-11721, doi: 10.5194/acp-12-11695-2012.

Sheridan, P.J., Andrews, E., Schmeisser, L., Vasel, B., and Ogren, J.A., 2016: Aerosol Measurements at South Pole: Climatology and Impact of Local Contamination, *AAQR*, **16**, 855-872, doi:10.4209/aaqr.2015.05.0358.

Sherman, J. P. and McComiskey, A., 2018: Measurement-based climatology of aerosol direct radiative effect, its sensitivities, and uncertainties from a background southeast U.S. site, *Atmos. Chem. Phys.*, **18**, 4131-4152, https://doi.org/10.5194/acp-18-4131-2018.

Sherman, J.P., Sheridan, P.J., Ogren, J.A., Andrews, E., Hageman, D.C., Schmeisser, L., Jefferson, A., and Sharma, S., 2015: A multi-year study of lower tropospheric aerosol variability and systematic relationships from four North American regions, *Atmos. Chem. Phys.*, **15,** 12487-12517, https://doi.org/10.5194/acp-15-12487-2015.

Shinozuka, Y., and Coauthors, 2015: The relationship between cloud condensation nuclei (CCN) concentration and light extinction of dried particles: indications of underlying aerosol processes and implications for satellite-based CCN estimates, *Atmos. Chem. Phys.*, **15**, 7585-7604, https://doi.org/10.5194/acp-15-7585-2015.

Sinha, P.R. and Coauthors, 2017: Evaluation of ground-based black carbon measurements by filter-based photometers at two Arctic sites, *J. Geophys. Res.*, **122**, 3544-3572, doi:10.1002/2016JD025843.

Skeie, R.B, Berntsen, T., Myhre, G., Pedersen, J.A., Strom, J., Gerland, S., and Ogren, J.A., 2011: Black carbon in the atmosphere and snow, from pre-industrial times until present, *Atmos. Chem. Phys.*, **11**, 6809-6836, https://doi.org/10.5194/acp-11-6809-2011.

Sorribas, M., Andrews, E., Adame, J.A., Yela, M., 2017: An anomalous African dust event and its impact on aerosol radiative forcing on the Southwest Atlantic coast of Europe in February 2016, *Sci. Tot. Environ.*, **583**, 269-279, https://doi.org/10.1016/j.scitotenv.2017.01.064.

Sorribas, M., Ogren, J.A., Olmo, F.J., Quirantes, A., Fraile, R., Gil-Ojeda, M., Alados-Arboledas, L., 2015: Assessment of African desert dust episodes over the southwest Spain at sea level using in situ aerosol optical and microphysical properties, *Tellus B*, **67**, doi: https://doi.org/10.3402/tellusb.v67.27482.

Spracklen, D. V., and Coauthors, 2010: Explaining global surface aerosol number concentrations in terms of primary emissions and particle formation, *Atmos. Chem. Phys.*, **10**, 4775-4793, https://doi.org/10.5194/acp-11-10661-2011.

Stone, R.S., Anderson, G.P., Andrews, E., Dutton, E.G., and Shettle, E.P., 2007: Incursions and radiative impact of Asian dust in northern Alaska, *Geophys. Res. Lett.*, **34**, doi:10.1029/2007GL029878 .

Titos, G. and Coauthors, 2017: Spatial and temporal variability of carbonaceous aerosols: Assessing the impact of biomass burning in the urban environment, *Sci. Tot. Environ.*, **578**, 613-625, doi:10.1016/j.scitotenv.2016.11.007.

Uttal T., and Coauthors, 2016: International Arctic Systems for Observing the Atmosphere: An International Polar Year Legacy Consortium, *Bull. Amer. Meteor. Soc.*, **97**, 1033-1056, https://doi.org/10.1175/BAMS-D-14-00145.1.

Wang, R., and Coauthors, 2018: Representativeness error in the ground-level observation networks for black carbon radiation absorption, *Geophys. Res. Lett*.,doi:10.1002/2017GL076817.

WCCAP, 2018: World Calibration Centre for Aerosol Physics, Accessed 21 May 2018, http://www.wmo-gaw-wcc-aerosol-physics.org.

Wiedensohler, A., and Coauthors, 2012: Mobility particle size spectrometers: harmonization of technical standards and data structure to facilitate high quality long-term observations of atmospheric particle number size distributions, *Atmos. Meas. Tech.*, **5,** 657-685, doi:10.5194/amt-5-657-2012.

Wilcox, J.D., 1956: Isokinetic Flow and Sampling, *J. Air Poll. Contr. Assoc.*, **5**, 226-245, doi: 10.1080/00966665.1956.10467715

WMO, 2011: WMO/GAW Standard Operating Procedures for In-situ Measurements of Aerosol Mass Concentration, Light Scattering and Light Absorption, GAW Report No. 200, World Meteorological Organization, Geneva, http://library.wmo.int/pmb_ged/gaw_200.pdf.

WMO, 2016: WMO/GAW Aerosol Measurement Procedures, Guidelines, and Recommendations, GAW Report No. 227, World Meteorological Organization, Geneva, https://library.wmo.int/opac/doc_num.php?explnum_id=3073.

WMO, 2018: Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications, WMO Report No. 1215, World Meteorological Organization, Geneva, https://www.wmo.int/pages/prog/arep/gaw/documents/Low_cost_sensors_post_review_final.pdf.

Yu, F. and Hallar, A.G., 2014: Difference in particle formation at a mountaintop location during spring and summer: implications for the role of sulfuric acid and organics in nucleation, *J. Geophys. Res.*, **119**, 12246-12255, doi:10.1002/2014JD022136.

Zanatta, M. and Coauthors, 2016: A European aerosol phenomenology-5: Climatology of black carbon optical properties at 9 regional background sites across Europe, *Atmos. Environ.*, **145**, 346-364, http://dx.doi.org/10.1016/j.atmosenv.2016.09.035.

Table 1. Description of aerosol parameters mentioned in text

Aerosol Parameter (symbol)	**Description of parameter and measurement instrument or equation for calculating**
Aerosol Light Scattering (σ_{sp})	Indicator of aerosol amount and related optical effects. Measured in the FAN with an integrating nephelometer.
Aerosol Light Absorption (σ_{ap})	Indicator of particle darkness; related to black carbon (BC). Measured in the FAN with a filter-based absorption photometer.
Aerosol Number Concentration (N)	Indicator of local contamination; precursor of cloud condensation nuclei. Measured in the FAN with a condensation particle counter.
Scattering Ångström exponent (SAE)	SAE describes the wavelength-dependence of scattered light. When scattering is dominated by sub-micrometer particles the SAE values are typically around 2, while SAE values closer to 0 occur when the scattering is dominated by particles larger than a few micrometers in diameter. $SAE = -\log[\sigma_{sp}(\lambda_1)/\sigma_{sp}(\lambda_2)]/\log(\lambda_2/\lambda_1)$
Single-scattering albedo (SSA)	SSA describes the relative contributions of scattering and absorption to the total light extinction. Purely scattering aerosols (e.g., sulfuric acid) have SSA values of 1, while very strong absorbers (e.g., elemental carbon) have SSA values around 0.3. $SSA = \sigma_{sp}/(\sigma_{sp} + \sigma_{ap})$

Figure Captions

Figure 1. Map of current and former long-term sites in FAN network superimposed on a nighttime lights image (Credit: NASA Earth Observatory/NOAA NGDC). Former sites RSL, SGP and WSA were FAN collaborations, while THD and SMO were solely NOAA observations.

Figure 2. Annual aerosol climatology for long-term sites in network. Stations are ordered by increasing scattering coefficient. (a) scattering coefficient; (b) absorption coefficient; (c) scattering Ångström exponent (d) single-scattering albedo. Scattering and absorption have units of Mm^{-1}, scattering Ångström exponent and single-scattering albedo are unitless. Values are reported at 550 nm, scattering Ångström exponent is calculated for the blue/green wavelength pair. Whiskers represent 5^{th} and 95^{th} percentiles, edges of box are 25^{th} and 75^{th} percentiles and midpoint line in box is median value of annual climatology. Blue indicates NOAA observatories, red indicates collaborator sites. Some sites are not shown due little available data (e.g., less than a year of data available or data not yet being QC'd).

Figure 3. Long-term climatology of aerosol light scattering (at 550 nm) in units of Mm^{-1} at Bondville. (a) monthly variability as function of year; (b) diurnal variability as function of month (thick black horizontal line indicates local noon). Both plots are based on data obtained from 1995 through 2016.

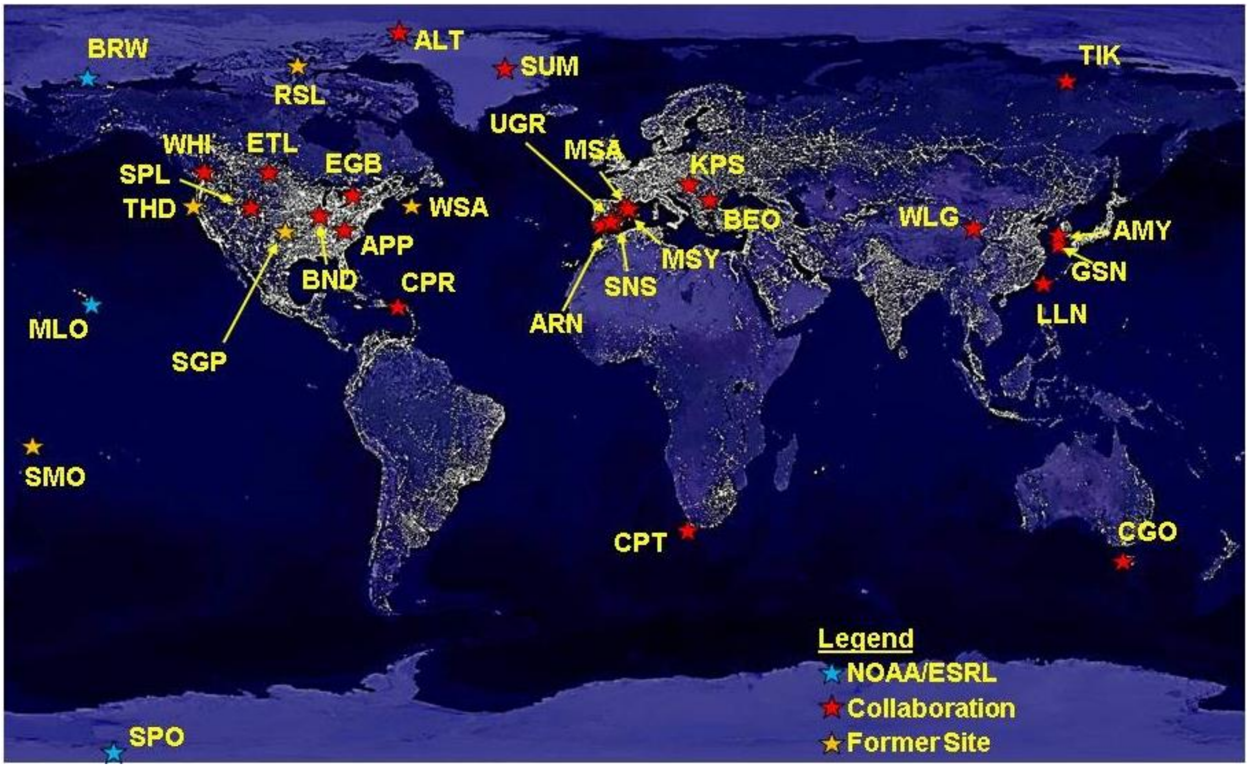

Figure 1. Map of current and former long-term sites in FAN network superimposed on a nighttime lights image (Credit: NASA Earth Observatory/NOAA NGDC). Former sites RSL, SGP and WSA were FAN collaborations, while THD and SMO were solely NOAA observations.

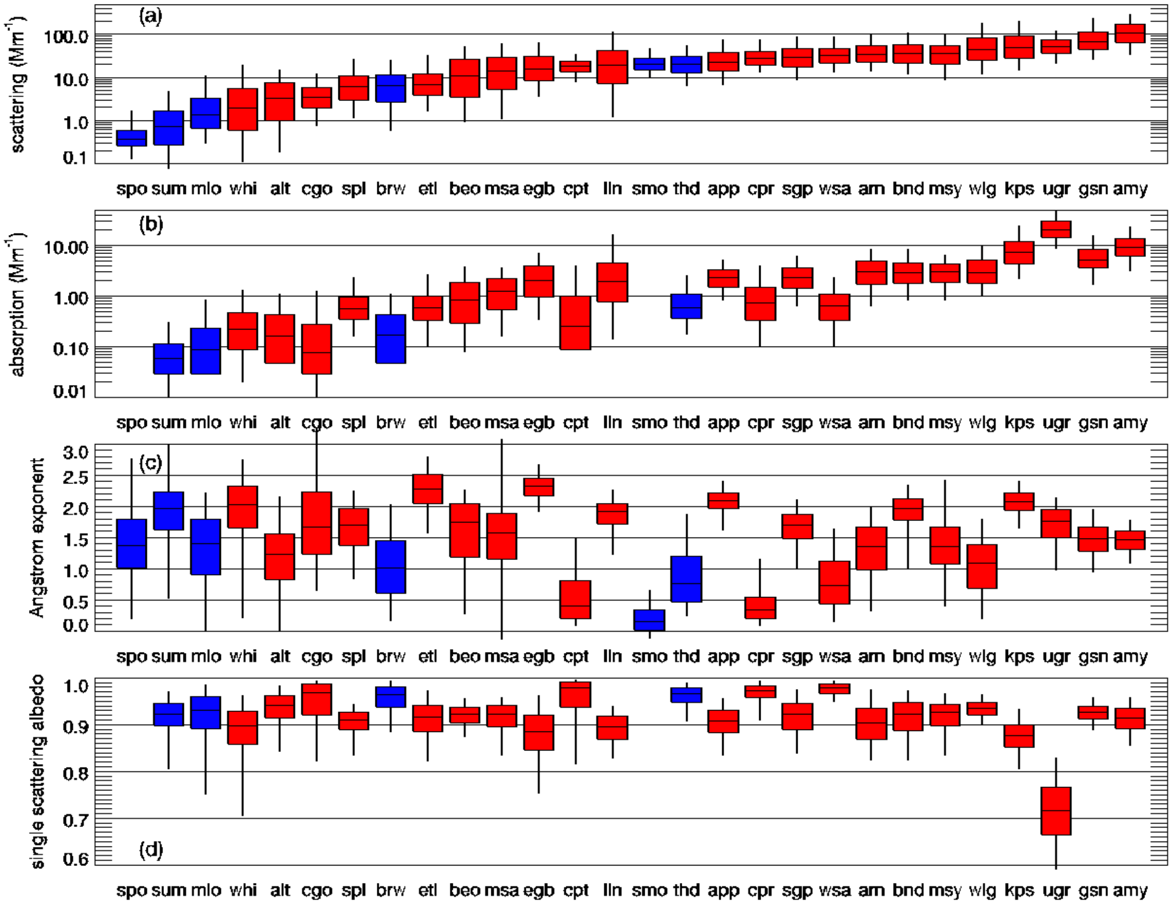

Figure 2. Annual aerosol climatology for long-term sites in network. Stations are ordered by increasing scattering coefficient. (a) scattering coefficient; (b) absorption coefficient; (c) scattering Ångström exponent (d) single-scattering albedo. Scattering and absorption have units of Mm^{-1}, scattering Ångström exponent and single-scattering albedo are unitless. Values are calculated from daily averages reported at (or adjusted to) 550 nm, scattering Ångström exponent is calculated for the blue/green wavelength pair. Whiskers represent 5th and 95th percentiles, edges of box are 25th and 75th percentiles and midpoint line in box is median value of annual climatology. Blue indicates NOAA observatories, red indicates collaborator sites. Some sites are not shown due to little available data (e.g., less than a year of data available or data not yet being QC'd).

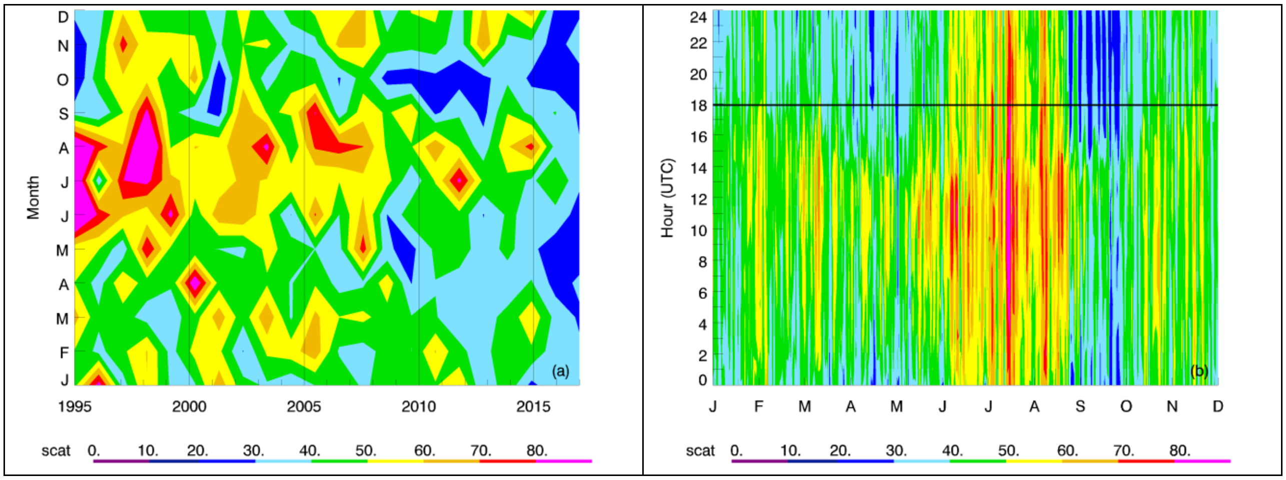

Figure 3. Long-term climatology of aerosol light scattering (at 550 nm) in units of Mm^{-1} at Bondville. (a) monthly variability as function of year; (b) diurnal variability as function of month (thick black horizontal line indicates local noon). Both plots are based on data obtained from 1995 through 2016.