SAM-CAAM

A Concept for Acquiring Systematic Aircraft Measurements to Characterize Aerosol Air Masses

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SAM-CAAM aims to characterize particle properties statistically with systematic, aircraft in situ measurements of major aerosol air masses, to refine satellite data products and to improve climate and air quality modeling.

Since 1995, the Intergovernmental Panel on Climate Change (IPCC) assessment reports have highlighted, as leading uncertainties in understanding Earth's climate, the direct impact of airborne particles on the planetary energy balance and the indirect effects they have on clouds, atmospheric stability, regional circulation, and the hydrologic cycle. For example, the confidence with which future climate can be predicted depends to first order on the relationship between the near-surface warming response and the radiative forcing, primarily by greenhouse gases and aerosol effects. This relationship is characterized, in its simplest form, as a linear factor—the climate sensitivity. The quantity is determined using present-day and retrospective values of forcing and response;

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currently, the largest uncertainty in climate sensitivity is due to uncertainty in the aerosol forcing (IPCC 2013; Schwartz et al. 2014; Forster 2016).

Further, the presence of aerosols often necessitates large corrections to other space-based measurements of independent parameters, such as ocean color and productivity (e.g., Gordon 1997), and they cause greater premature mortality than ozone, NO_x, or other pollutants (Lelieveld et al. 2015). Frequent, global aerosol airmass-type mapping, of value itself for air quality, material transport, and other applications, also represents critical test, validation, and constraint data for climate modeling. Here, we expand the definition of "aerosol type" normally used in satellite remote sensing, which covers those categorical distinctions among particle components and mixtures that can be made from optical constraints, of varying sensitivity, to particle size, shape, and spectral absorption. To these we add particle hygroscopicity, mass, and composition, which are critical for treating aerosol direct and indirect forcing in climate models and for air quality applications. These additional characteristics cannot be derived from remote sensing alone and thus require in situ measurement. Further, measurements of these quantities make it possible to better represent aerosol light-absorption properties needed to address many radiative and dynamical questions, yet cannot be retrieved with sufficient accuracy from satellite observations alone.

Single-view satellite instruments, such as the NASA EOS Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS), retrieve primarily aerosol optical depth (AOD), a measure of aerosol column amount, while providing little or no constraint on aerosol type, except via AOD spectral dependence over water (see appendix for list of acronyms). Retrieval algorithms for these instruments must assume aerosol scattering and absorption properties to derive even AOD from measured radiances (e.g., Levy et al. 2007). Several other space-based instruments have demonstrated greater capability to map aerosol airmass types globally. About a dozen aerosol types can be distinguished under good retrieval conditions from the EOS Multi-angle Imaging SpectroRadiometer (MISR). The multiangle, multispectral data reflect *qualitative* differences in retrieved particle size, shape, and single-scattering albedo (Kahn et al. 2010; Kahn and Gaitley 2015). The EOS *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*) two-wavelength lidar can identify six aerosol types from attenuated backscatter and volume depolarization ratio, plus some general geographical constraints, amounting to qualitative, vertically resolved classifications (Omar et al. 2009). Adding polarization to multiangle, multispectral passive remote sensing, for example, with the European Space Agency's Polarization and Anisotropy of Reflectances for Atmospheric Sciences Coupled with Observations from a Lidar (PARASOL) or a next-generation satellite instrument, promises to improve the number of aerosol airmass-type distinctions that can be made and to broaden the range of conditions under which such mapping can be done (Mishchenko and Travis 1997; Hasekamp and Landgraf 2007; Dubovik et al. 2011). Yet, even these remote sensing improvements are unable to adequately constrain aerosol characteristics treated in advanced climate models.

Aerosol properties retrieved from surface-based remote sensing, such as those from AERONET sun photometers, make important contributions to aerosol-type climatology (e.g., Dubovik et al. 2002). But in addition to affording only sparse spatial sampling, they suffer from uncertainties and limitations common to most passive retrieval techniques, as they report only column-effective rather than layer-resolved or component-resolved properties. For most aerosol properties, AERONET also requires solar zenith angle > 50° and total-column AOD at 440 nm (AOD_{440}) > 0.4 to obtain good-quality constraints (which at most locations skews the sampling toward the highest AOD conditions) and must assume the indices of refraction for all but one aerosol mode in the column (Dubovik and King 2000).

At present, it seems unlikely that particle microphysical and chemical properties can be retrieved from remote sensing measurements alone at the level of accuracy required to substantially reduce uncertainties in total direct aerosol radiative forcing (DARF), its anthropogenic component, aerosol–cloud interactions, horizontal material transports, surface–atmosphere aerosol fluxes, and air quality–related applications (e.g., IPCC 2007, 2013). For example, it is estimated that constraining DARF to ~1 W m^{-2} requires midvisible AOD and SSA, both dimensionless quantities, to be known to an accuracy of ~0.02 (McComiskey et al. 2008; Chin et al. 2009; Loeb and Su 2010), which is beyond the capabilities of current satellite instruments. SSA is helpful for qualitative aerosol source attribution, such as identifying anthropogenic components, and is key to simulating atmospheric heating profiles and cloud evolution, especially in polluted or smoky environments, as well as broader effects on atmospheric circulation and regional water cycles. However, even advanced future remote sensing instruments will only loosely constrain SSA, and near-surface speciation for health effects cannot be derived solely from remote sensing data. Mass extinction efficiencies (MEEs) are required to translate between remote sensing–derived particle optical properties and aerosol mass, the fundamental quantity tracked in air quality, aerosol transport, and climate models. However, MEEs must be derived from in situ particle composition and size distribution measurements; otherwise, they are estimated by modeling these factors, or simply assumed. Lacking direct measurements for validation in most cases, only very loose bounds exist on MEE values and uncertainty. For example, the MEE for black carbon (BC) particles assumed globally within 20 leading AeroCom aerosol transport models ranges from 5.3 to 18.9 $m^2\ g^{-1}$; for dust the values range from 0.46 to 2.05 $m^2\ g^{-1}$; and even for sulfate, the MEE values adopted vary by a factor of 7 (Chin et al. 2009, Table 3.2; Kinne et al. 2006). Yet available measurements are unable to resolve these differences, much less to provide the range of likely MEE values for BC and other particle types from different sources or of different exposure ages. Similarly, hygroscopicity (particle water uptake), required to account for humidity-dependent particle optical property changes as well as particle activation conditions that mediate cloud formation, cannot be derived from remote sensing observations except under special conditions (e.g., Pahlow et al. 2006; Rosenfeld et al. 2016), and there is very limited data covering the range of likely values for different particle types in different situations.

So there remains a need for better particle optical, microphysical, and chemical property constraints, including region- and source-specific SSAs, hygroscopicities, and MEEs needed to constrain climate and air quality models and to improve the linkages between satellite data and models. However, for most aerosol sources and specified seasons, emitted and evolved particle microphysical and chemical properties tend to be repeatable, due to relatively unchanging fuel or reservoir type and other persistent environmental factors. For example, the amounts of wildfire smoke from Alaskan boreal forests and desert dust from the Bodele Depression vary dramatically over time, but the particle properties at each of these sources remain relatively constant, because they arise from the same material, via the same physical mechanisms. Similarly, particle evolution downwind, due to chemical reactions, changes in hydration state and/or changes in microphysical properties through processes such as coagulation tend to be mediated by climatologically similar environmental conditions. These important simplifying attributes mean that an airborne observing program designed to routinely measure particle properties in situ could capture probability distribution functions (PDFs) of particle intensive properties (i.e., properties that do not depend on the amount of aerosol), characterizing the major aerosol airmass types in the detail needed to adequately address the major aerosol- and climate-related questions. An additional advantage of aircraft observations is that flight plans can be designed to sample both near source and downwind, to capture at least the typical changes particles undergo during transport.

Several aircraft campaigns have demonstrated the value of making systematic aerosol measurements and, to an extent, the feasibility of an operational aircraft program targeting aerosol properties (e.g., Andrews et al. 2011; Sheridan et al. 2012; Matvienko et al. 2014). Both in situ and some surface remote sensing measurements to date do provide important constraints that are used by the satellite community in aerosol retrieval algorithms (e.g., Levy et al. 2007; Omar et al. 2009; Kahn et al. 2010; Russell et al. 2014). Some aircraft field campaigns have deployed instrument packages that include a large fraction of the implied measurement suite; however, comprehensive and extensive statistical characterization of aerosol type has not been their primary focus. For example, quantities such as MEE are generally not constrained in these experiments, and the level of effort required to sample many aerosol types multiple times is typically beyond the scope of such campaigns. SAM-CAAM aims at filling this need, taking advantage of technological advances, and is motivated in part by the increasingly long satellite aerosol data record.

A database of aerosol airmass-specific particle optical, microphysical, and chemical property PDFs, combined with frequent, global aerosol airmass-type maps derived from satellite observations and surface measurements where available, would provide the next major advance in constraining chemical transport models used to calculate the regional and global radiation fields, material fluxes, and climate impacts (e.g., Kahn 2012). It would improve the aerosol products derived from current satellite observations by providing better aerosol climatology assumptions for the retrieval algorithms. In addition, measurement-based MEEs would place the integration of satellite-retrieved optical properties with aerosol transport, air quality, and climate models on more solid ground, adding considerable value to several decades of existing as well as future satellite aerosol data. The SAM-CAAM data would thus allow the field to advance significantly even with existing satellite data and would provide context and impetus for future space-based aerosol missions.

What follows is a concept paper. Having discussed the need for certain systematic constraints on aerosol properties, the next section identifies the variables

TABLE 1. Required variables. Instrument types for payload option C are given in brackets under each variable; abbreviations are listed in the appendix. Note that the variables listed here are required to reduce the uncertainties in key geophysical quantities derived from remote sensing, such as aerosol amount and type, and cloud condensation nuclei occurrence, as well as in using these quantities to constrain climate and air quality models. Specific example instruments for all four payload options are given in the online supplement.

I. Aerosol properties derived from the integrated analysis of in situ measurements
1. Spectral extinction coefficient (EXT)
To constrain satellite AOD retrievals [six-channel, three-color CRD (two size cuts: 1 and 10 μm; four channels at low RH) + two for #3 GRO]
2. Spectral absorption (ABS) or single-scattering albedo
To constrain AOD retrievals and to determine atmospheric absorption and heating {dual three-channel filter absorption (two size cuts: 1 and 10 *μ*m at low RH) [matched to (#1 EXT), (#6 PHA)] + refractory carbon}
3. Particle hygroscopic growth factor (GRO)
To connect particle properties over the full range of instrument and ambient RH conditions [two-channel CRD (from #1 EXT) at high RH + humidified OPC and PI-nephelometer]
4. Particle size (SIZ) (at least three bins in number concentration, though detailed size distribution probably needed to meet primary objectives)
As a complement to chemical composition discrimination; required for deriving #7 MEE [SMPS + Fine-OPC + Coarse-OPC + Active inlet to 50% at 10 *μ*m]
5. Particle composition (CMP)
For source identification To classify measurements in terms of aerosol type as specified in most models, e.g., sea salt, sulfate, mineral dust, BC, brown carbon, especially important for aerosol–cloud interaction modeling To support deriving the anthropogenic fraction, which is needed to calculate direct aerosol "climate" forcing from space-based retrievals, and for air quality applications CMP would be constrained by analysis of detailed chemical and/or microphysical properties, such as elemental carbon (EC) concentration and particle shape [Dual filter stations (two size cuts)]
6. Spectral single-scattering phase function (PHA) [all possible angles]
To constrain multiangle radiance AOD retrievals To calculate radiation fields Polarized: to help determine aerosol type, and to constrain remote sensing observations where polarized data are included [PI-Nephelometer + dryer/humidifier, with PM_{10} size range and three wavelengths matched to #1 EXT and #2 ABS]
7. Mass extinction efficiency (MEE)
To translate between optical remote sensing measurements and model parameters Derived from integrated analysis of particle size distributions, with density deduced from particle compositional constraints [derived from integrated analysis of measured variables]
8. Real Refractive Index (RRI)
To constrain AOD retrievals to the level of detail required for aerosol forcing [inverted from PI-Nephelometer (from PHA #6) and Open-I-Nephelometer (from A-EXT #12)]
II. Variables providing meteorological context
9. Carbon monoxide (CO; also possibly CO_2, NO_2, O_3)
As a tracer for smoke, to help distinguish smoke from urban pollution in some cases [Cavity ringdown CO and NO_2 ICOS spectrometers + O_3]
10. Ambient temperature (T) and relative humidity (RH)
To help interpret ambient measurements To translate between instrument and ambient conditions [T, P, RH]
11. Aircraft 3D location (LOC)
To relate aircraft measurements to any available satellite observations, and to model simulations [GPS]

Table 1. Continued.
III. Variables providing ambient, remote sensing context
12. Ambient spectral single-scattering phase function (A-PHA) [all possible angles]
To constrain remote sensing AOD retrievals and assess in-aircraft measurements by comparing with ambient conditions
To help calculate radiation fields
Polarized: to help determine aerosol type, and to constrain remote sensing retrievals where polarized data are included
[Open-I-Nephelometer + external CRD + surf. sun photometer and lidar targets of opportunity]
13. Ambient spectral extinction coefficient (A-EXT)
To constrain remote sensing AOD retrievals and assess in-aircraft measurements by comparing with ambient conditions
[Open-I-Nephelometer (from A-EXT #12) + internal PI-Nephelometer (from #6 PHA) dry reference]
14. Large particle/cloud probe (A-CLD)
To provide some information about dust and other particles larger than the inlet size cut
As an independent measure of possible cloud impact on the reliability of other data
[Small Droplet Probe + Ice Probe]
15. Aerosol layer heights (HTS)
To determine flight levels for subsequent direct sampling
To correlate with meteorological conditions
As a constraint on trajectory modeling to identify aerosol sources and evolution
[airborne backscatter lidar]

required to meet the SAM-CAAM objectives and discusses the feasibility of implementing such a project by identifying some example instrument technologies and broader payload options capable of making the required measurements. The next section covers mission-related factors such as the possible organization for an operational aircraft program; flight planning; and data handling, distribution, and analysis. Prospects for achieving the goals of SAM-CAAM are summarized in the final section.

IMPLEMENTATION. SAM-CAAM can integrate with available satellite data records and ongoing chemical transport modeling programs as part of the overall effort to characterize the environmental roles aerosols play. The aircraft-measurement component aims to obtain layer-resolved aerosol microphysical and chemical properties, to the extent possible within the constraints of a single, relatively small aircraft. The larger goal is to acquire enough in situ measurements of major aerosol airmass types to construct PDFs of their key properties. This effort draws upon the aerosol aircraft community to provide instruments and data products and the satellite measurement and aerosol modeling communities to offer context for the measurements and to develop climatologies of aerosol airmass-type space–time distribution. It requires the combined expertise of all these communities to interpret the data, assess tradeoffs as needed to efficiently meet the observational objectives, and implement the results in a range of applications. In general, satellites can map the distribution of aerosol air masses, the in situ data can contribute the microphysical and chemical detail associated with these air masses, and models can interpolate and extrapolate based on physical and chemical principles and parameterizations to create a consistent picture.

Required variables. Several overriding considerations mediate the specification of required variables. These are motivated by the need to constrain specific aspects of satellite aerosol retrievals and of applying satellite data to models, as summarized in Table 1. They were determined prior to consideration of any particular measurement technologies. As multiple aerosol types commonly reside at different elevations within the atmospheric column, the SAM-CAAM in situ measurements must be layer resolved. To the extent possible, they should be aerosol-component resolved, or at least size resolved into fine and coarse fractions, to isolate the unique properties of aerosols within layers having different origins and histories. (Coarse mode aerosols are generally considered to have diameter > 1 μm and tend to be dominated by mineral and soil dust, as well as sea salt, whereas fine mode usually means submicrometer aerosols, such as most smoke, biogenic, and pollution particles.) To capture the diversity in particle optical properties, the observations need to be wavelength resolved, providing at least three values spanning the spectral range of ~440–870 nm for reflected solar radiation retrievals, down to ~350 nm and up to ~1.6 or even 2.3 μm if possible. To translate among different humidity conditions, both ambient and instrument-specific, and to provide key information for particle hydration and aerosol–cloud interaction analysis and modeling, the RH dependence of aerosol extinction, absorption, and scattering properties is needed. And, as inlet sampling biases become progressively more severe for particles larger than ~1 μm in aerodynamic diameter (i.e., coarse mode particles), measurements made outside the aircraft should be included where possible.

To address these broad requirements, we identified a total of 15 required variables. We organized them into three groups, to provide a convenient way of representing some fundamental differences in the types of measurements involved:

1) aerosol properties obtained from the integrated analysis of in situ measurements made within the aircraft;
2) variables providing ancillary, meteorological context; and
3) quantities providing ambient remote sensing context, made directly (except the layer height, which is made by remote sensing).

The required variables and their relevance to the SAM-CAAM objectives are summarized in Table 1. The in situ measurement suite obtains key aerosol properties through direct measurement of many quantities under controlled conditions within the aircraft. Some values that cannot be measured directly, such as aerosol mass extinction efficiency, are derived through the integrated analysis of measured quantities. As such, there is no one-to-one correspondence between required variables and measurement technologies. The integrated analysis aims to derive quantities in as many ways as possible to improve quality assessment and validation and to estimate uncertainties.

The variables providing meteorological context are needed to relate the measured and derived aerosol properties to the conditions in which the particles reside, and the quantities providing remote sensing context are needed to remove ambiguities and limitations of the within-aircraft measurements, by making some measurements under ambient conditions. So, for example, if the spectral extinction coefficient is measured under ambient conditions, the value can be compared with the extinction coefficient measured under controlled RH conditions after calculating the implied hydrated particle properties at ambient RH using the measured RH and particle hygroscopic growth factor. Similarly, large particles will be better represented in the ambient measurements, and particle-size-dependent inlet efficiency affecting the in-aircraft instruments can be assessed, which is especially important if only a passive inlet is available for within-aircraft measurements.

Payload options. An instrument payload that can be flown routinely and relatively economically at least several times per week would be assembled, targeting the required variables listed in Table 1. [An aerosol-related aircraft program of this type, but with somewhat different objectives and a smaller payload, was successfully demonstrated in the past by Andrews et al. (2011).] SAM-CAAM would build upon this experience. To mitigate the challenge of acquiring the needed resources and to avoid the conundrum of ever-increasing project requirements (mission creep), we identified four payload options of increasing ambition, with the understanding that for most measurements, a final payload will probably fall somewhere between an "option A" technology that might barely help constrain a required variable and an "option D" capability that could exceed the demands of the primary SAM-CAAM objectives.

Just to test the feasibility of the SAM-CAAM concept, we first assembled a substantial list of instrument options for each required measurement and then assessed the "latitudinal tradeoffs," a process aimed at identifying up to four technologies that could address each required variable to different degrees of accuracy and/or completeness. To close the notional payload options definition process, we subsequently evaluated the "longitudinal tradeoffs," which amounted to assessing the capabilities and technical resource costs (weight, power, aircraft integration requirements, and degree of autonomy) for each payload option overall and reconsidering the selected example technology options, aiming for balance between the relative contributions of each measurement to the fundamental goals of SAM-CAAM and the associated resource requirements. So rather than a single "science traceability matrix" identifying the connections between specific science objectives, measurement requirements, and technologies, this process resulted in effectively four such matrices, offering a broad spectrum of mission and de-scope options that meet the SAM-CAAM objectives to varying degrees. A summary of some candidate instruments for each example payload option, based on the results of this exercise, is given in the online supplement (http://dx.doi.org/10.1175/BAMS-D-16-0003.2).

Payload option A identifies available technologies that minimally address in some way the required variables but in most cases do not actually meet the spirit or the letter of the SAM-CAAM objectives. Specifically, particle optical properties would be acquired only at a single wavelength, particle mass required to derive MEE is not obtained, and coarse mode particles, such as the dominant components of most natural dust and sea salt aerosol size distributions, would not be sampled effectively beyond an EPA $PM_{2.5}$ standard (e.g., McNaughton et al. 2007). Thus, payload option A provides a useful lower bound on a payload definition effort, but it lacks sufficient capability to meet the SAM-CAAM objectives.

Option B would meet the SAM-CAAM requirements, but only for fine mode aerosols. It includes multispectral and particle mass constraints, along with RH dependence for #6 PHA particle phase function (see Table 1 for the abbreviations and number designations of the required variables), and ground-based sun photometer and lidar to provide some integral constraints on the in situ measurements, at least at one location. However, the aircraft must fly vertical spirals to determine the elevation of aerosol layers elsewhere, and the passive inlet together with the option B in situ instrument suite leave the aerosol coarse mode undersampled for several variables and unsampled for most. Among the optical properties measured internally, size cuts are not provided. An external cloud probe #14 A-CLD would report ambient sub- and supermicrometer fractions, but not properties, so only some indication of the unsampled particle types would be available.

Payload option C includes an active inlet, which enables coarse mode particle sampling from within the aircraft (Huebert et al. 2004). As such, this option essentially meets the key SAM-CAAM objectives. Size cuts would be provided for #1 EXT, #2 ABS, and #3 GRO, and #4 SIZ would be enhanced to include sensitivity to an EPA PM_{10} standard. Option C would also provide significantly improved sensitivity to black carbon for #2 ABS and particle shape information from #14 A-CLD, which would identify mineral dust. An airborne backscatter lidar is included in option C for #15 HTS, a substantial advantage for flight planning, as the elevations of layers to be sampled would be obtained without flying multiple vertical spirals.

Payload option D offers capabilities that could be of great significance to aerosol–climate and air quality research in general, but extend beyond those required to meet the main SAM-CAAM objectives. For example, several airborne remote sensing instruments could be included, such as an SSFR and/or mini 4STAR for #12 A-EXT and A-ABS, and airborne HSRL for #15 HTS. (If deployed on a single aircraft, the flight-planning strategy for a payload including both in situ and remote sensing instruments would be challenging because of competing observing requirements.) With existing technologies, #1 EXT could be measured in the ultraviolet (UV) and near-infrared in addition to visible wavelengths; #2 ABS could be measured more directly; #3 GRO hygroscopicity could be isolated to specific aerosol components; more redundancy and/or tighter constraints could be obtained for #4 SIZ, #5 CMP, #6 PHA, #10 RH, #13 A-PHA, and #14 A-CLD; and organic aerosol precursor gases could be measured for #9 tracers. These options are included in Table ES1 in the online supplement to illustrate the possibilities, in case support to deploy one or more such advanced instruments becomes available for other reasons, and provided the added operational requirements do not detract from the primary mission objectives. Alternatively, such enhanced capabilities might be part of independent payloads flown separately as part of field campaigns, with which SAM-CAAM might coordinate, as appropriate, when the opportunity arises.

Payload option C best meets the SAM-CAAM objectives. We list example instrument types for this option after each variable in Table 1 to illustrate the possibilities. As the majority of aerosol extinction is found at altitudes < 5 km, an aircraft capable of extensive, efficient operation at low-to-mid altitude would be favored for the SAM-CAAM objectives, and the slower aircraft speeds of a turboprop compared to a turbojet aircraft would reduce sampling artifacts. A preliminary evaluation of instrument space, weight, and power requirements, based on the notional payload in Table ES1, suggests that the payload option C would be too large for a Twin Otter–sized aircraft and would not effectively use the much larger capacity of a P-3 Orion. In the online supplement, we present a straw-man integration scenario on a Shorts C-23B Sherpa aircraft to demonstrate the feasibility of accommodating payload option C in aircraft of this class.

MISSION-RELATED CONSIDERATIONS.

Unlike typical aircraft field campaigns, SAM-CAAM must be organized to support routine operations, continuing over many months or years to obtain adequate sampling over major aerosol airmass types. As such, site selection and flight planning must be streamlined, and instrument maintenance, data handling, and deployment decision-making need to function as seamlessly as possible. Mission design must aim to limit high-risk activities along the critical data acquisition path and to avoid potential data-handling bottlenecks as much as possible. Initial considerations in these areas are outlined in this section.

Deployment site selection and completion strategies. The SAM-CAAM program would begin by sampling the aerosol airmass types accessible from the payload integration site, possibly NASA's Wallops Flight Facility (WFF) in Virginia, where the host aircraft might originate. Starting operations at the instrument integration site would facilitate a convenient shakedown and testing period for aircraft, payload, and data system. WFF, for example, would provide access to aerosol airmass types from the central, eastern, and southeastern United States, including sources from several large urban areas; biomass burning and biogenic particles from Canada and the southeastern United States, primarily in summer (e.g., Clarke et al. 2007); maritime particles from the Atlantic; and soil dust from points west, especially in spring (Fig. ES1).

As this is an endeavor of global scope, the value of the SAM-CAAM measurements increases multifold as more aerosol air masses are characterized. So after studying the region accessible from a given site, the aircraft would move to another base of operations, sample the aerosol airmass types accessible from that location, and continue. The aircraft could be stationed successively at about three or four sites per year, for approximately 12 weeks at each, and might target as many as four or five aerosol air masses from judiciously selected sites. As such, subsequent deployment sites would be selected based on monthly, global maps of aerosol airmass-type climatologically likely locations derived from aerosol transport modeling, combined with knowledge of suitable basing facilities. Locations from which three or more regionally to globally important aerosol airmass types could be sampled would be preferred. As an example, Fig. ES1 in the online supplement shows the climatological AOD within ~500 km of the NASA WFF, for six aerosol types during the spring and summer seasons, as simulated by the Community Atmosphere Model, version 5 (CAM5; Liu et al. 2012). Black carbon, primary and secondary organics, and sulfate are maximal in this region during the summer, whereas mineral dust and sea salt peak in spring. A formal approach could include combined principal component analysis of the daily model-simulated or satellite-retrieved burdens of multiple aerosol components in candidate deployment regions (e.g., Li et al. 2013).

The decision about when an aerosol airmass type has been adequately sampled by the aircraft would be based primarily upon adaptive criteria, as such criteria might be required to obtain statistically representative results, for example, once the variance in the accumulated PDFs of the key measured quantities diminishes below certain values. However, a combination of adaptive criteria and practical considerations would probably be needed, whereby an absolute criterion, determined from deployment site availability, cost, and seasonal meteorology, would limit the maximum duration of the deployment at a given station, and adaptive criteria would help set the targeting frequency for different aerosol airmass types accessible to the aircraft from that station. As a very rough estimate, an average of three flights per week, at about 6 h per flight, for 8 weeks of flying amounts to just under 150 h per deployment site.

Flight planning. A relatively simple flight planning process is needed to facilitate routine operations. As such, nominal flight plans targeting the climatological locations of each accessible aerosol air mass would be predetermined for a given deployment site. These would also overfly any relevant ground stations, such as AERONET, lidar, or radiation measurement sites, where appropriate. A day before flights, a designated lead planner would review meteorological data, available aerosol model predictions, and status of the sampling history and select a primary and possibly a backup flight plan. The selection, along with a brief rationale, would be posted to the SAM-CAAM website by a specified hour before the flight, for any comments from the team. Nominal flight plans would entail flying out at high altitude to obtain aerosol-layer heights from, for example, the airborne, nadir-viewing lidar of payload C, then sampling the layers systematically, generally extending from near source to some distance downwind to capture particle evolution, and then returning to the airfield. As needed, adjustments to the predetermined flight plans would be identified in advance of implementation to the extent possible, to limit the complexity of the flight operations routine. Data download to the ground might be required to make any real-time flight decisions. The payload could occasionally also be flown within the field of view of satellite instruments, to allow intercomparison and, to the degree possible, cross validation of in situ and remote sensing results (e.g., Kahn et al. 2004; Reidmiller et al. 2006). However, satellite coordination would not be required to meet the primary objectives of SAM-CAAM, and, for example, the required in situ sampling would be possible under nonprecipitating, cloudy conditions. Brief deployments could study nearby targets of opportunity, such as major wildfires, or allow participation in larger, shorter-term field campaign efforts that include multiple aircraft and address a broader range of scientific objectives, including column radiation closure. However, the SAM-CAAM program would not be contingent upon such opportunities.

Instrument maintenance. Unlike many field campaigns, SAM-CAAM will require instruments that can make reliable measurements with a small technical staff to maintain the payload most of the time. The individual instrument teams would assist with the initial installation and debugging of instrument protocols and would train the payload technicians in any required pre- or postflight checkout, cleaning, reporting procedures, routine calibration, or other maintenance. More substantial servicing or emergency repairs would have to be dealt with by the instrument teams as needed.

As typical turnaround times for addressing small instrument anomalies and performing routine maintenance are 1–3 days, two or three flights per week could be reasonably accommodated by a dedicated two- or three-person technical ground crew for payload options up to option C. One of the challenges presented by payload option D is that many advanced instruments require considerably more scientist and/or technician involvement in the field.

Data acquisition, product generation, and distribution. SAM-CAAM flights would generate a wealth of science data from a suite of about 20 instruments, covering aerosol microphysical, optical, and chemical properties as well as related gas-phase tracers, meteorological parameters, and aircraft state variables. Management of the SAM-CAAM data will build upon experience from NASA satellites, field campaigns, and surface networks. The overarching goals are to operationally generate high-quality, integrated data products having well-characterized uncertainty values, to preserve the resulting scientific data records, to quickly distribute data products to the research community, and to maintain adequate documentation.

The SAM-CAAM aircraft would be equipped with a central data system similar to those on other NASA research aircraft, to facilitate data communication and feed standard UTC time and aircraft location to each instrument. In addition, a data server would be required to store the output from each instrument, including the primary output and ancillary data needed for data processing. This will streamline and automate the data transfer process to a ground-based central processing server after each flight. The total data volume is estimated to be less than 10 TB per year. The onboard data server would also be used to stream limited datasets to instrument and flight scientists on the ground or in the aircraft. This information allows for any real-time decisions required by the flight scientist for better execution of the flight plan.

Following the NASA EOS model, most SAM-CAAM data would be processed at a central site such as the Atmospheric Science Data Center (ASDC) at the NASA Langley Research Center to facilitate operational throughput, using instrument-team-developed algorithms and software. Instrument principal investigators (PIs) would be responsible for delivering standard product-generation code and updating it as needed. The PIs would also be responsible for maintaining their data processing codes at their home institutions for algorithm development, testing, and validation.

Data products would be routinely posted and made available through the project website, much the way the AERONET sun and sky scanning photometer network operates (Holben et al. 1998; http://aeronet.gsfc.nasa.gov/). Preliminary data would be released to the instrument teams, until the minimum time required to routinely generate good-quality data is determined. These data would be used primarily to check instrument performance and provide a quick look at the sampled aerosol layers. After a shakedown period, the SAM-CAAM project would aim to release initial data products to the community with a latency of between about 24 h and a week, and final products within about 3–6 months of each flight, on a continuing basis. This is an aggressive schedule compared to typical airborne field campaigns, but it is preferred because of the operational nature of the data stream. The SAM-CAAM data products could be released in both International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) and Network Common Data Form (netCDF) formats.

The SAM-CAAM data products would be archived at an assigned data center chartered for long-term preservation and distribution of satellite and airborne atmospheric Earth science data. To enhance data usability, the assigned center would create merged datasets with aircraft navigational data so that all data products would be geolocated, as is done for many field campaign measurements [e.g., Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS) and Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ)]. Web-based tools for searching, downloading, and merging tools (similar to those at http://tad.larc.nasa.gov) would be developed or adopted, tailored to the SAM-CAAM datasets. In addition, visualizing and subsetting tools would be developed to handle the SAM-CAAM-specific datasets as needed. Subsetting would be based on geographical, temporal, and aerosol airmass-type criteria.

Integrated data analysis. Some quantities will need to be derived from several coincident measurements, such as #7 MEE, which is obtained from #1 EXT and #5 CMP. Integrated analysis algorithms can also derive certain quantities several different ways, depending on measurement redundancy in the payload. Independent derivations would make advanced error and uncertainty analysis possible and would contribute to data quality assessment. The example of the ambient spectral extinction coefficient is given in the "Deployment site selection and completion strategies" section above, assuming payload C is flown. Overflights of surface remote sensing stations and occasional coordination with other aerosol aircraft campaigns could provide independent measurements needed to assess the overall quality of the in situ data and could help determine whether the required variables are being measured with sufficient accuracy (e.g., Moore et al. 2004).

Subsequent data analysis would include studying the detailed aircraft products in the context of corresponding satellite and aerosol transport model interpretations of the aerosol airmass types sampled by the flights. This consideration helps motivate a near-term schedule for beginning SAM-CAAM operations, as several current satellite instruments capable of making large-scale aerosol airmass-type observations, such as MISR and CALIPSO, are operating well beyond their design lives. The data analysis effort would evolve, with the aim of gaining experience at merging spacecraft, suborbital, and model results into a more complete and accurate picture of atmospheric aerosols and their environmental impacts.

Payload and deployment program evolution. A shakedown period would be required for the payload and data stream, in some cases initially in the laboratory, and then after aircraft integration. For example, the absorption coefficient of coarse mode–dominated dust aerosols measured by filter-based absorption instruments such as the CLAP would need to be verified in laboratory tests, because their response to dust aerosols, and the associated correction algorithms, might not yet meet SAM-CAAM requirements. The integrated instrument suite would then need to be operated during flight and inlet-to-instrument lag times determined, so aerosol-type coincidence can be established; size-specific particle losses or enhancements evaluated to the extent possible; and data processing, quality assessment, and integrated analysis schemes tested and refined. Several iterations would likely be required before the payload is ready for routine research flights.

Some instrument development, aimed, for example, at miniaturization, more autonomous operation, increased accuracy, or lower maintenance requirements, could contribute to the evolution of the payload and might be motivated by the limitations of existing technology options. Occasional payload upgrades might be implemented as improved technologies become available. It is critical to the overall success of a SAM-CAAM effort that the measurements be traceable and repeatable, so potential replacement instruments would initially be flown in tandem with the existing instruments and coincident data would be collected and evaluated to assure continuity of the data record. As such, the aircraft would need to have modest excess capacity to accommodate temporary payload expansion.

Continuing, high-level strategic decisions about the evolution of the aircraft payload and deployment program would be made by a project science panel, responsible for the overall success of the SAM-CAAM effort, led by a project scientist. This group could include the instrument PIs, modelers, satellite and surface measurement scientists, and other key participants with expertise relevant to all aspects of the measurement and analysis effort.

PROSPECTS. The primary objectives of SAM-CAAM are to develop a statistical database of major aerosol airmass-type properties, to improve and add detail to the assumptions made in aerosol remote sensing retrieval algorithms and air quality and climate models (including quantitative constraints on particle light-absorption properties), and to provide comprehensive aerosol hygroscopicity and mass-extinction efficiency measurements to place those generally assumed in aerosol transport and climate modeling on firmer footing. Direct validation of specific satellite aerosol retrievals would be desirable when possible, but would be lower priority, as the in situ measurements can be made with clouds above and/or below the aerosol layers, conditions that preclude some remote sensing retrievals, and routine coordination would significantly complicate SAM-CAAM flight planning. Similarly, model validation can proceed by direct comparison with the aircraft measurements and comparisons with satellite products that are informed by the particle optical properties and MEEs obtained statistically from SAM-CAAM. The latter is the higher priority, as the objective of the project is to characterize the major aerosol air masses statistically, thereby allowing improvement of both models and satellite products.

Evidently, there are at least three distinct perspectives on aerosol "type" in general climate and air quality applications: 1) as derived from space and ground-based remote sensing, which amounts to a classification based on retrieved optical properties (often column effective rather than layer resolved), that constrain ambient size, shape, SSA, and refractive indices; 2) as observed from in situ measurements of aerosol microphysical, chemical, and optical properties, often at modified temperature and humidity; and 3) as represented in models, wherein aerosol amount and type are defined by emitted mass and assumed or estimated particle microphysical properties, based on source inventory characteristics and parameterized particle evolution. The SAM-CAAM measurements would take a major step toward interrelating these three perspectives, helping create a unified aerosol picture for climate simulation, air quality assessment, and other applications.

As AERONET was initiated to support aerosol measurements from EOS, SAM-CAAM could be implemented in part to support a future mission, such as the NASA Decadal Survey's Aerosol–Cloud–Ecosystem (ACE) mission (National Research Council 2007). Also, similar to the AERONET structure, international entities might eventually deploy analogous aircraft payloads as part of a federated system. If so, they could contribute their data to the central product-generation site for standard processing and distribution, thereby increasing the global sampling of aerosol airmass types.

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APPENDIX: LIST OF ACRONYMS. Numbers in parentheses indicate entries in the required measurements and payload options tables. Literature citations and web addresses are included, as available. Note that acronyms from the supplemental material are included in this list as well.

AERONET	The Aerosol Robotic Network of surface-based sun and sky-scanning photometers (Holben et al. 1998)
AMS	Aerodyne mass spectrometer (#5 CMP) (www.aerodyne.com/products/aerosol-mass-spectrometer)
AOD	Aerosol optical depth
BS/TS	Backscatter/total-scatter nephelometer (#3 GRO)
CAPS-SSA	Cavity attenuated phase shift spectrometer (#1 EXT) (www.aerodyne.com/products/caps-pmssa-monitor; www.aerodyne.com/products/caps-pmex-monitor)
CARIBIC	Civil Aircraft for the Regular Investigation of the Atmosphere Based on an Instrument Container (#5 CMP) (Nguyen et al. 2006; Andersson et al. 2013; www.caribic-atmospheric.com)
CDP	Cloud droplet probe (#14 A-CLD) (www.dropletmeasurement.com/products/airborne/CDP-2)
CIP	Cloud imaging probe (#14 A-CLD)
CLAP	Continuous light absorption photometer (#2 ABS)
COBALD-type sonde	Compact Optical Backscatter Aerosol Detector (#13 A-PHA) (www.iac.ethz.ch/groups/peter/research/Balloon_soundings/COBALD_sensor)
COTS	Commercial, off-the-shelf, i.e., commercially available
CRD	Cavity ring-down optical spectrometer (#1 EXT) (www.picarro.com/technology/cavity_ring_down_spectroscopy)
DMT-UHSAS	Droplet Measurement Technologies Ultra-High Sensitivity Aerosol Spectrometer (#4 SIZ) (www.dropletmeasurement.com/products/ground-based/UHSAS)

EOS	NASA's Earth Observing System
EPA $PM_{2.5}$	Environmental Protection Agency standard, particulate matter smaller than 2.5-μm diameter
EPA PM_{10}	Environmental Protection Agency standard, particulate matter smaller than 10-μm diameter
FAA	Federal Aviation Administration
Gerber PVM	Gerber particle volume, surface area, and effective radius measurement (#14 A-CLD) (www.gerberscience.com/pvmaspecs.html)
GPS	Global Positioning System
GRIMM 1.129	GRIMM Aerosol Spectrometry Sky OPC (#4 SIZ)
HOLODEC	Holographic Detector for Clouds (#14 A-CLD) (Baumgardner et al. 2011)
HSRL	High-spectral-resolution lidar (#15 HTS)
HTDMA	Hygroscopic Tandem Differential Mobility Analyzer (#3 GRO) (www.brechtel.com/HTDMA_brochure.pdf)
ICOS	Integrated Cavity Output Spectrometry (Paul et al. 2001)
LWC	Cloud liquid water content (#14 A-CLD)
MEE	Particle mass extinction efficiency (#7 MEE)
MPL	Micro-pulse lidar (#15 HTS)
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research (Boulder, CO)
NOAA	National Oceanographic and Atmospheric Administration
OPC	Optical particle counter (#3 GRO)
Open-INeph	UMBC open (to the atmosphere) imaging nephelometer (#13 A-PHA)
PA	Photo-acoustic analyzer (#2 ABS)
PCASP	Passive cavity aerosol spectrometer probe (#14 A-CLD) (www.dropletmeasurement.com/products/airborne/PCASP-100X)
PI-Neph	UMBC polarized imaging nephelometer (#6 PHA) (Dolgos et al. 2009; https://airbornescience.nasa.gov/instrument/PI-Neph)
PTR-MS	Proton transfer reaction–mass spectrometry (#9 CO, tracers) (Hansel et al. 1995; www.ionicon.com/information/technology/ptr-ms)
RH	Relative humidity
SAM-CAAM	Systematic Aircraft Measurements to Characterize Aerosol Air Masses
SID2H	Small Ice Detector Version 2 (#14 A-CLD) (http://data.eol.ucar.edu/codiac/dss/id=107.003)
SMPS	Scanning mobility particle sizer spectrometer (#4 SIZ) (www.tsi.com/scanning-mobility-particle-sizer-spectrometer-3936/)
SP2	Single particle soot photometer (#2 ABS) (www.dropletmeasurement.com/sites/default/files/ManualsGuides/SP2/Operator.pdf)
SSA	Single-scattering albedo
SSFR	Solar spectral flux radiometer (#12 A-EXT)
4STAR	Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (#12 A-EXT)
TSI-LAS	TSI Inc. laser aerosol spectrometer (#4 SIZ) (www.tsi.com/laser-aerosol-spectrometer-3340/)
UH	University of Hertfordshire
UMBC	University of Maryland, Baltimore County
UW	University of Washington
WELAS	White light scattering aerosol spectrometer (#4 SIZ) (www.filterintegrity.com/PTAS/PandS/Products/welasmain.html)
WHOPS	White-light humidified optical particle spectrometer (#3 GRO) (www.psi.ch/lac/eu-pegasos; http://eu-pegasos.blogspot.com/p/psi-rack.html)
WVSS	Atmospheric Water Vapor Sensing System (#10 T; P; RH) (www.spectrasensors.com/wvss/)

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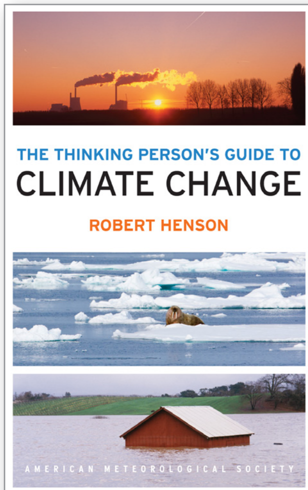

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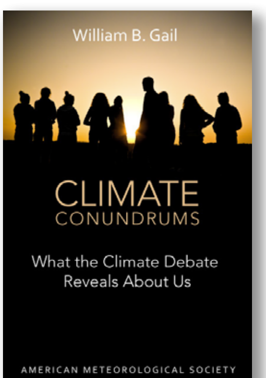

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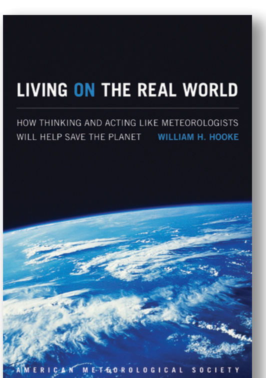

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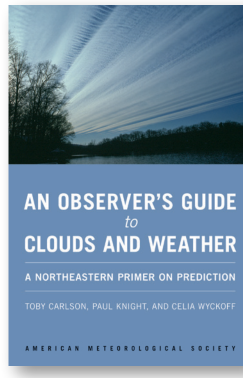

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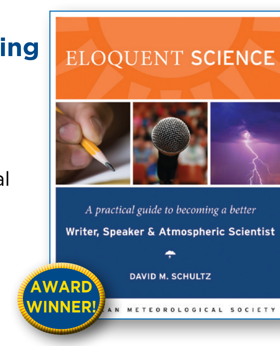

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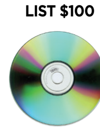

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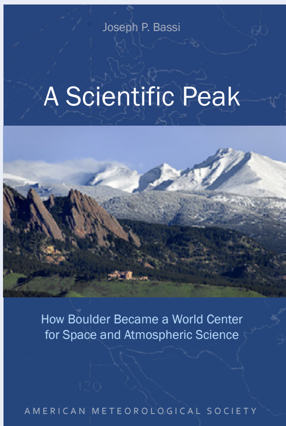

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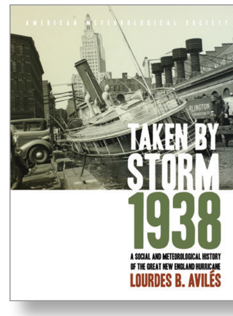

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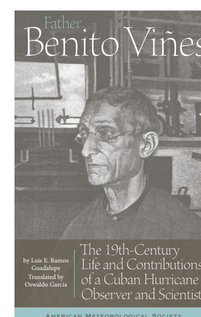

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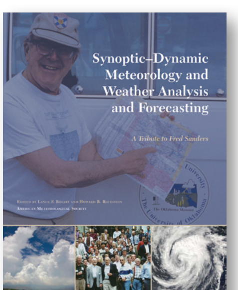

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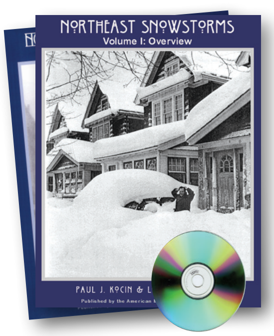

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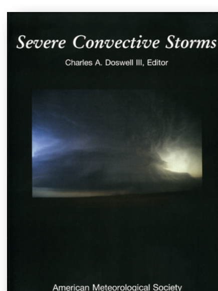

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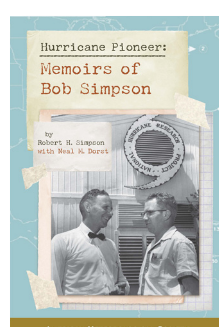

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