PARAGON: A Systematic, Integrated Approach to Aerosol Observation and Modeling

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Aerosols are generated and transformed by myriad processes operating across many spatial and temporal scales. Evaluation of climate models and their sensitivity to changes, such as in greenhouse gas abundances, requires quantifying natural and anthropogenic aerosol forcings and accounting for other critical factors, such as cloud feedbacks. High accuracy is required to provide sufficient sensitivity to perturbations, separate anthropogenic from natural influences, and develop confidence in inputs used to support policy decisions. Although many relevant data sources exist, the aerosol research community does not currently have the means to combine these diverse inputs into an integrated data set for maximum scientific benefit. Bridging observational gaps, adapting to evolving measurements, and establishing rigorous protocols for evaluating models are necessary, while simultaneously maintaining consistent, well understood accuracies. The Progressive Aerosol Retrieval and Assimilation Global Observing Network (PARAGON) concept represents a systematic, integrated approach to global aerosol characterization, bringing together modern measurement and modeling techniques, geospatial statistics methodologies, and high-performance information technologies to provide the machinery necessary for achieving a comprehensive understanding of how aerosol physical, chemical, and radiative processes impact the Earth system. We outline a framework for integrating and interpreting observations and models and establishing an accurate, consistent and cohesive long-term data record.

I. Introduction

Aerosols exert myriad influences on the Earth's environment and climate and on human health. Scattering and absorption of sunlight[1], modification of cloud properties[2,3], effects on regional precipitation[4,5], adverse consequences for human respiratory health[6,7], and degradation of visibility in parks and wilderness areas[8] are among the ways in which aerosols affect the Earth's energy balance and the availability and quality of our water and air.

Many groups have published assessments of aerosol-climate interactions and highlighted the considerable uncertainties associated with them[1,7,9-15]. A fundamental goal is to understand the sensitivity of the climate system to increasing abundances of greenhouse gases. Without quantifying aerosol forcing (and other critical factors, such as cloud feedbacks) to a high level of accuracy, it is not possible to evaluate the performance of climate models over the industrial period, and yet it is these same models that are relied upon for decisions regarding adaptation to a changing climate and/or mitigation of the consequences. The uncertainties associated with the ability of three-dimensional global models to predict both natural and anthropogenic aerosol forcing, as a function of time and location, make it critically important to validate and improve models through comparison with measurements.

No single type of observation or model is sufficient to characterize the current atmospheric system or to provide the means to predict aerosol impacts in the future with high confidence. Information must be drawn from multiple sources and vantage points, and strategies that explicitly plan for integration of the data need to be designed. Because physical and chemical processes occurring on microphysical scales influence aerosol regional and global climatic and environmental impacts, linkages between data acquired on vastly different spatial and temporal scales must be made in order for models to capture aerosol transformation processes with high fidelity. Consistency of observations over time is essential for detection of long-term change.

II. Aerosol data sources

Data sources cover the wide range of spatial and temporal scales upon which aerosol-related processes operate, and include active and passive satellite sensors, solar and sky radiometer networks, chemistry and microphysics networks, lidar networks, mobile platforms (aircraft and ships), laboratory measurements, intensive field campaigns, integrated observing facilities, and chemical transport models. Understanding the relative strengths and limitations of data sources is a prerequisite to establishing an effectively integrated program. For example:

a. Satellites can measure the 3-D distribution, radiative impact, and spatial context of airmasses, and provide regional and global views. However, determining size-resolved composition exceeds current satellite capabilities.

b. Remote sensing is subject to indeterminacies that make it difficult to separate the effects of variables such as particle shape, composition, internal heterogeneity, absorptivity, abundance, size distribution, and vertical distribution. Combinations of techniques are required.

c. Active techniques, such as lidar, are excellent at constraining certain properties (notably vertical distribution), but typically provide point (from the ground) or single-track (from orbit) profiling measurements only.

d. Knowledge of chemical composition is required to understand the processes relating aerosol optical properties and concentrations to emissions. *In situ* airborne sensors provide detailed information about particle microphysics and chemical composition that are unachievable through other means, but their coverage is limited.

e. Atmospheric models, such as general circulation models (GCMs) and chemical transport models (CTMs) provide global diagnostics and forecasts that can calculate aerosol compositional and microphysical properties that are difficult to determine observationally. GCMs incorporate important aerosol physics, but do not provide the real-time meteorological consistency that is that is inherent in CTMs; the latter, on the other hand, may ignore feedbacks between atmospheric chemistry and meteorology.

III. Challenges facing aerosol research

The aerosol community does not currently have the means to combine the vast array of data into an integrated set. A long-term solution to this problem requires the ability to bridge observational gaps and adapt to changes in measurement approaches, while maintaining consistently well-understood accuracies. We identify four challenges that must be dealt with in order to reduce model uncertainties.

Integrating multivariate and multidimensional information from diverse sensors and models is necessary to adequately characterize aerosols. These data have nonuniform spatial and temporal sampling and coverage, and originate from many sources. No single source of data captures all essential information at all relevant scales. A comprehensive description of the global aerosol system requires cohesion of diverse inputs, and a strategy is needed for identifying, prioritizing, and obtaining measurements in undersampled regions. Significant effort needs to be expended in data and model intercomparison and validation to gauge the reliability of the results. Practical means of interpreting the resulting multidimensional, multivariate, and massive informational data bases are needed.

The current level of accuracy and consistency among aerosol observations and models is insufficient to meet the needs of climate research, and there are critical observational gaps. No unified plan exists to generate a cohesive, long-term aerosol record with consistent quality and accuracy. Obtaining radiometric measurements having adequate accuracies remains a significant observational challenge. The finite durations of satellite missions, with different sensors employing different techniques, makes it difficult to separate technology, calibration, and algorithm evolution from climate trends. With some exceptions (e.g., surface solar radiometers and *in situ* particle samplers), there are few long-term standards with which to evaluate product accuracies.

The inhomogeneity of aerosol sources and sinks, coupled with their relatively short atmospheric residence time, implies that estimation of global climate forcing by aerosols must involve integrating highly variable quantities over space and time. A practical framework for merging data acquired over a wide span of spatial and temporal scales needs to be established. Spatial and temporal variability are primary causes of the large uncertainty in calculations of aerosol climate forcing. The mesoscale variability of tropospheric aerosols occurs on scales finer than generally resolved by CTMs and by measurements with long sample times. For example, chemical samples accumulated on a 24-hour or longer basis do not always represent instantaneous aerosol properties measured from satellites. Currently, the paucity of *in situ* data aloft prevents the exploration of key processes at sub-grid scales.

Because clouds complicate the aerosol retrieval process, and are major climate forcing agents, conclusions regarding aerosol-induced climate and environmental changes require simultaneous cloud data, along with a means of isolating aerosol-cloud interactions from other meteorological variability. Effective cloud screening is essential for determining direct aerosol forcing. Moreover, microphysical characterizations must be supplemented by three-dimensional radiative transfer approaches to account for the effects of cloud morphology, intercloud illumination, and shadowing. Isolating indirect forcing effects can be complicated by scattered light from nearby clouds, the effects of subpixel clouds, and meteorological correlations between cloudiness and pollution.

IV. The proposed initiative

In our view, the most effective way of dealing with the challenges enumerated above, and accelerating the rate of progress in aerosol research, is to take a systematic approach to aerosol and climate research, as others have suggested[16-18]. Implementation of this approach can be promoted by combining multiple observational techniques and modeling capabilities into a cohesive framework, taking advantage of data synthesis methodologies and high-performance information technologies. The proposed initiative is named the Progressive Aerosol Retrieval and Assimilation Global Observing Network (PARAGON). We focus specifically upon two key areas: *integrating and interpreting observations and models*, and *establishing an accurate, consistent, and cohesive long-term record.*

A. Integrating and interpreting observations and models

Data aggregation and synthesis are required to organize satellite data together with concurrently acquired *in situ* (e.g., airborne) and surface-based remote sensing data, and must be adaptable to a changing measurement complement. As new data capture increasingly detailed descriptions of aerosol properties and distributions, an evolving level of sophistication will make it possible to tackle problems of increased difficulty. Specific recommendations are presented in the following paragraphs.

Assemble a worldwide "aerosol virtual observatory" to promote widespread exchange and use of data, and take advantage of high-performance computing to enhance processing power for global modeling. The first step in making data widely accessible is to assemble an organizational infrastructure. Modern information technology approaches will benefit PARAGON through the use of "grid"[19] and other high-performance computing initiatives to establish a distributed aerosol science information system, or "virtual observatory". Aerosol researchers can capitalize on the experience of astronomers[20] and high energy physicists[21], among others. Massively parallel or other high-performance computing approaches could be explored as a potential means of improving the spatial and temporal resolution of global models as a complement to sub-grid-scale parameterizations.

Develop methodologies for integrating observational and model data having diverse spatial and temporal sampling, resolution, and coverage. Given the diverse nature of aerosol measurements, data synthesis (combining measurements representing averages over different extents in space and time) provides the key to spanning the requisite multiplicity of scales. Geospatial statistics methods, such as Bayesian hierarchical modeling[22], provide a rigorous, data-driven approach to this problem. Another approach is assimilation[17], which incorporates models of aerosol physics. The latter are required in order to use the aggregated data to make forecasts based on observations. Data assimilation can use an assembled aerosol data set directly, or use the integrated data provided by a geospatial statistics framework.

Invest in algorithm development and validation to support joint retrievals using data from existing and future satellite, surface-based, and in situ sensors. Two examples of the potential benefits of combining data from multiple sensors as part of a joint retrieval process include the simultaneous use of satellite- and surface-based multiangle measurements of scattered radiance[23] and the combination of passive and active sensor data[24]. Greater accessibility of diverse data can stimulate algorithm developments leading to new scientific capabilities.

Explore data summarization and mining techniques to identify and interpret patterns of aerosol-induced change. Describing the observed evolution of complex, non-linear relationships among multiple parameters is critical to climate model improvement and validation. Making sense of the complexity and volume of aerosol data demands summarization to facilitate wide-scale interpretation and extraction of patterns contained within the data. Efficient interpretation can take advantage of modern statistical and data mining techniques. Recent advances in these fields provide templates from which specific methods customized for aerosol science can be derived[25,26].

Establish approaches to compare chemical transport and radiative model outputs with observations in a systematic way, and generate rigorous metrics for quantifying discrepancies in order to identify model or measurement deficiencies. Lack of integration between models and measurements is one of the main difficulties confronting the aerosol research community. Resolving discrepancies between them requires establishing a comparison strategy that can isolate how well each process involved in the lifecycle of aerosol layers is modeled[27]. Statistical hypothesis testing provides a useful guide to quantifying agreement between observed and modeled data distributions.

B. Establishing an accurate, consistent, and cohesive long-term record

A long-term system of aerosol observation requires sustainable accuracy, consistency, and resources. Continuity needs to be assured through robust calibration, validation, and measurement and model intercomparison programs. Cohesiveness of the complement of measurements is required such that surface-based, airborne *in situ*, and satellite observations observe the same parcels of air on the relevant temporal and spatial scales. Specific recommendations are presented in the following paragraphs.

Invest in research and technologies to improve sensor calibration, and develop systematic methods for validating aerosol optical and microphysical parameters obtained from remote-sensing instruments. An important component of PARAGON is the development and application of techniques for consistent evaluation of the uncertainties in measured and modeled aerosol properties. Independent observations and analyses for each key climate parameter are essential due to the difficulty of achieving climate quality accuracy with most instruments, the need to verify surprising climate change results, and the large economic and social impacts of climate change. Improvements in calibration accuracy and stability are required broadly across climate instruments[28]. Closure experiments[29], which seek agreement between measured and calculated aerosol properties, and environmental snapshots from intensive field campaigns[30], are essential for validating results from instruments with wider areal coverage, and strategies for generating validation data on an ongoing basis need to be developed.

Provide stable funding for surface-based radiometer, chemical, and lidar networks; expand coverage into key undersampled areas; upgrade measurement capabilities; and establish routine in situ aircraft observations at selected sites, coincident with satellite overpasses. Accurate, quality-assured point observations of aerosol optical depth are widely available; however, uncertainties of column-integrated microphysical parameters need to be routinely assessed against *in situ* observations. Because it is important to sample mid-ocean areas downwind of continental plumes, as well as in pristine areas, continued seaborne measurements[31] are needed. A lidar network with proper global distribution of stations requires extending existing networks[33,34] into data-sparse regions, transition to advanced instruments, and installation of a common data quality assurance program. Synergistic networks that combine optical depth, spectral directional sky radiance, microphysical property retrievals, and *in situ* capabilities need to be expanded. Several enhancements in chemical sampling data are essential to evaluating and improving CTMs. A program of sustained airborne measurements will be particularly helpful in supporting process studies, validation, and demonstrations of coherency between model predictions and remote-sensing observations[35].

Develop advanced satellite imagers and lidars to reduce indeterminacies in aerosol microphysical property retrievals, and investigate the sensitivity of passive methods to height information where active measurements are unavailable. Combining multispectral, multiangular, and polarimetric imaging techniques into a unified sensor can minimize uncertainties in column-integrated aerosol properties owing to each method's unique sensitivities to particle microphysics[36]. Lidars provide the most accurate measurements of the vertical distribution of aerosol absorption, but the natural variability of tropospheric aerosols makes a pure backscatter lidar approach problematic due to ambiguities in separating backscatter and extinction. High spectral resolution and Raman lidar techniques derive profiles of these two quantities more directly[37]. The former is on a credible technology path toward space-based deployment and the latter is viewed as the best method for implementation of a ground-based network.

Adopt a systems approach to the development of new satellite missions, factoring the integration of satellite measurements, surface and suborbital data, and models explicitly into instrument and mission design. Orbit selection affects satellite instrument capabilities such as sampling frequency of given locations (e.g., surface and *in situ* instrument emplacements), global coverage time, and synergy between passive and active approaches. This systems view requires taking into account how the various elements of a global observing network are to be designed and situated, and demands a level of coordination and planning that currently does not exist.

V. Conclusions

Achieving the PARAGON vision requires establishing multidisciplinary, interagency, and international partnerships, and enfranchising diverse segments of the aerosol community. The concept involves a marriage of aerosol observations with assimilation and chemical transport modeling, information technology, geospatial statistics, and data mining research. A systematic, coordinated program to understand the current atmospheric state and to evaluate and improve models will accelerate the process by which scientists and policy makers can achieve a deeper understanding of the impact of aerosols on global and regional climate change and air quality.

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