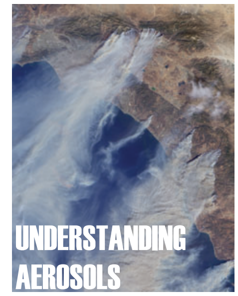

Aerosol Data Sources and Their Roles within PARAGON

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An integrated observing and modeling system should take full account of the strengths and limitations of diverse aerosol data sources.

The data supporting aerosol research can be obtained either observationally or indirectly from models. Observations can be broadly divided into routine monitoring efforts, which may be used to continuously evaluate an assimilation model, or episodically generated data, localized in space and/or time (Fig. 1). Assimilated monitoring results, if they require large model adjustments in certain areas or under certain conditions, offer obvious clues to poor model representations of the aerosol physics. Episodic data, produced for example by large, coordinated field campaigns, are typically not assimilated directly into models, but provide atmospheric snapshots containing detail, unobtainable elsewhere, to diagnose model performance and identify model deficiencies. Observations in both categories may also be aggregated into aerosol climatologies. The quality of the resulting product depends on having tools to integrate data with different spatial and temporal sampling characteristics, and the freedom to match the space–time resolution of the climatology to available data sampling. Good measurement design, including calibration, validation, and data acquisition strategy, are also factors.

In this paper, we review the sources of data that need to be brought together to support the goals of the Progressive Aerosol Retrieval and Assimilation Global Observing Network (PARAGON) initiative (Diner et al. 2004). We highlight data sources that provide aerosol properties in the atmosphere. Laboratory data are not covered, though these are important for understanding gas–particle conversion processes, heterogeneous chemistry, and particle optical properties.

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SATELLITES. Satellite radiometers measure regional and global radiances, from which both aerosol optical and microphysical properties, along with radiative fluxes, can be derived. Satellite imagers provide the most practical means to track long-range airmass transport and identify the spatial and temporal context. Retrievals of aerosol properties using spectral information over the ocean have progressed from an algorithm using a single Advanced Very High Resolution Radiometer (AVHRR) red band (Stowe et al. 1997), to two- and four-band visible/near-infrared

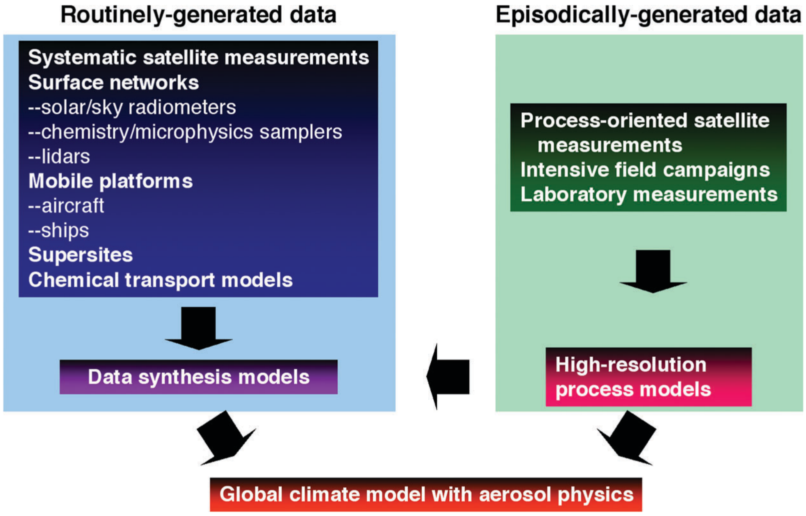

Fig. 1. Types of data and their respective roles relative to PARAGON.

approaches with AVHRR and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Mishchenko et al. 1999; Higurashi and Nakajima 2002). Satellite-based multispectral measurements exhibit sensitivity to particle-size distribution (e.g., King et al. 1978, 1999), an idea that was refined for the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol retrieval algorithm (Tanré et al. 1997). Inclusion of bands in the visible and shortwave infrared, in particular, provides discrimination between accumulation and coarse size modes (Remer et al. 2002). Over land, aerosol retrievals are complicated by the large variability in surface bidirectional reflectance. For dark surfaces, the MODIS algorithm combines visible and shortwave infrared measurements to retrieve aerosol optical depth (Chu et al. 2002; Kaufman et al. 1997, 2002). Near-ultraviolet mapping from the Total Ozone Mapping Spectrometer (TOMS) offers a unique approach in that most land surfaces are dark at these wavelengths, and the interaction between aerosol and Rayleigh scattering offers sensitivity to aerosol absorption and, to some extent, height (Torres et al. 2002). Unlike MODIS, which has a spatial resolution in the nadir of 1 km or better, the footprint of TOMS is several tens of kilometers.

Having multiangle as well as multispectral data provides additional constraints on both particle size and shape. For example, the Multiangle Imaging Spectroradiometer (MISR) instrument's nine cameras (Diner et al. 2002) cover a wide range of scattering angles centered around the side scattering direction, making it possible to separate spherical from randomly oriented nonspherical particles (Kahn et al. 1997, 2001; Kalashnikova et al. 2004). For typical ocean-viewing conditions, the MISR combination of spectral and angular coverage also provides sensitivity to three to five size groupings of particles (Kahn et al. 1998). Oblique slant paths through the atmosphere enhance sensitivity to thin aerosol and cirrus layers. Changing the geometric perspective provides three-dimensional views, making possible geometrical plume- and cloud-top-height retrieval (Moroney et al. 2002; Muller et al. 2002; Zong et al. 2002). Integration over an angle provides estimates of hemispherical reflectance (albedo), a key parameter for quantifying shortwave radiative forcing, more accurately than single-angle observations (Loeb and Davies 1996; Loeb and Coakley 1998). Sensors such as the Along-Track Scanning Radiometer (ATSR) successors (Stricker et al. 1995) have demonstrated the benefit of multiangle shortwave infrared observations, particularly for aerosol retrievals over land (Flowerdew and Haigh 1995, 1996; Veefkind et al. 1998; North et al. 1999; Robles González 2003). Over deserts and urban areas—major aerosol source regions—ground reflectance is high, and separating the surface and atmospheric radiance signals is challenging. MISR takes advantage of differing angular reflectance signatures of the surface and atmosphere to retrieve aerosol optical depth over such areas (Martonchik et al. 1998, 2002, 2004; Zhang and Christopher 2003).

Multiangle polarimetric data, particularly when acquired at both visible and shortwave infrared wavelengths, make it possible to retrieve the real part of the particle refractive index (Mishchenko and Travis 1997; Cairns et al. 1999; Chowdhary et al. 2001, 2002), which can serve as a coarse proxy for aerosol composition. Surface polarization tends to be spectrally neutral over land, which is an advantage for polarimetry (B. Cairns et al. 2003, personal communication). The Polarization and Directionality of the Earth's Reflectances (POLDER) (Deschamps et al. 1994) land aerosol algorithms retrieve an index that factors in aerosol optical depth and its spectral dependence (Deuzé et al. 2001). The aerosol polarimetric sensor (APS) instrument developed for the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) will produce nonimaging multiangle polarimetric measurements with an extremely high polarization accuracy.

Backscatter lidar operating at two or three wavelengths is currently the most detailed source of space-based aerosol vertical profiles, as demonstrated by the Lidar In-Space Technology Experiment (LITE) shuttle lidar (McCormick et al. 1993). LITE's ability to see aerosol and cloud spatial structure on a global scale, with vertical resolution around 100 m, created a strong interest in longer-duration backscatter lidar missions. Accordingly, the Geoscience Laser Altimeter System (GLAS) (Schutz 1998) was launched in early 2003, and the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Winker et al. 2002) will be launched as part of NASA's sun-synchronous afternoon "A Train."

SOLAR AND SKY RADIOMETER NETWORKS. Only in the last decade have surface-based radiometer networks developed the potential for continuous, long-term aerosol optical depth measurements. Some networks provide routine observations of additional radiometric parameters, such as directional spectral sky radiance and direct and diffuse solar flux. These measurements can be inverted, along with optical depth, to produce integrated radiative microphysical and optical properties (Nakajima et al. 1996; Dubovik and King 2000). The most extensive network of this type is an array of sunphotometers operated as the Aerosol Robotic Network (AERONET) federation (Holben et al. 1998). Under cloud-free conditions, AERONET reports daytime aerosol optical depth derived from direct-beam solar measurements (Holben et al. 2001). Under a more restrictive set of favorable observing conditions, the column-averaged particle-size distribution, single-scattering albedo, and complex index of refraction are derived from sky scans (Dubovik et al. 2002). AERONET aerosol optical depth results have been verified against aircraft and in situ observations (for theoretical accuracies, see Dubovik et al. 2000); however, uncertainties of column-integrated aerosol microphysical properties have not yet been systematically assessed against in situ data.

A sunphotometer network in east Asia (SKYNET) integrates solar flux and in situ aerosol measurements. In North America, several Multifilter Rotating Shadowband Radiometer (MFRSR) networks (e.g., Alexandrov et al. 2002; Bigelow et al. 1998) provide frequent optical depth observations. In addition, automated sunphotometers are taking high-quality optical depth observations internationally (Heimo et al. 1993; Mitchell and Forgan 2003; McArthur et al. 2003). These observations are sometimes complemented with in situ measurements. Microtops handheld sunphotometers have been used during field campaigns and in operational settings, though the data are considered unreliable for long-term monitoring [addressed in World Meteorological Organization (WMO) meeting in Davos, Switzerland, in March 2004]. NASA's Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program of shipboard observations is also a significant data source, but its continuation is currently in doubt.

Clearly, the infrastructure to produce accurate, quality-assured aerosol optical depth observations is presently available at numerous globally distributed sites (see network summary in Table 1). But many key programs lack long-term commitments for continued operation, and the development of more advanced observational networks, combining optical depth, spectral directional sky radiance, in situ, and lidar observations to create more complete environmental snapshots, has been slow.

CHEMISTRY AND MICROPHYSICS NETWORKS. Next in the spectrum of sampling density and measurement complexity are stations that focus on aerosol chemical composition. The most common are air-quality monitoring networks operated largely by regional and national environmental agencies (Malm et al. 1994; B. A. Schictel et al. 2003, personal communication), though some have been supported by universities and other organizations (e.g., Prospero 1999). A smaller number of advanced stations provide linked aerosol chemical, microphysical, and radiative property measurements. Such stations include networks supported by the Environmental Protection Agency (EPA), NOAA Climate Monitoring and Diagnostics Laboratory (CMDL), and the AsiaNet program, as well as selected sites in Australia, Ireland, Scandinavia, Germany, and Switzerland. The Atmospheric Brown Cloud program plans a multinational network, and the Baseline Surface Radiation Network (BSRN) and Global Atmospheric Watch (GAW) maintain some collocated radiative flux and in situ aerosol measurement sites. The data from these stations can be used to derive parameterizations of aerosol properties, such as the mass-scattering efficiency of major chemical species, particle hygroscopic growth factors, and cloud condensation nuclei (CCN) concentrations, for detailed comparison with model values. The stations require more on-site technical support than do those providing only optical depth and bulk chemistry; the greater operating costs limit their number to a few dozen globally. The GAW program is working to coordinate the measurements at

Table 1. Surface-based networks that have optical depth as a primary measurement.

Network	No. of sites	Spectral range (nm)	Observing frequency	Optical depth accuracy	Data access	Siting
AERONET (aeronet.gsfc.nasa.gov)	162	340–1600	15 min	±0.015	Excellent	Global
SKYNET (atmos.cr.chiba-u.ac.jp/aerosol/skynet)	8	400–1000	10 min	±0.03	Fair	East Asia
ASRC and SURFRAD (www.srrb.noaa.gov/surfrad)	10	415–870	20 s to 5 min avg	±0.02	Excellent	Regional (United States)
GAW (rea.ei.jrc.it/netshare/wilson/WDCA)	12	368–862	Hourly avg	±0.01	Fair	Global background
CMDL (www.cmdl.noaa.gov)	8	380–862	1 min	±0.015	Very good	Global background
USDA (uvb.nrel.colostate.edu)	33	368	20 s to 3 min avg	Analysis planned for 2004	Excellent	Regional (United States)
BSRN (bsrn.ethz.ch)	34	368–782	1 min	Program being implemented	Very good	Global background
BoM	16	412-862	1 min	±0.01	Poor	Regional (Australia)

existing sites, encourage expansion of the network, and establish research centers where data from many stations can be quantitatively compared.

Several enhancements to the typical suite of chemical sampling data would go a long way toward improving chemical transport model (CTM) validation. Chemical data acquired only at the surface inadequately constrain CTMs, which is one reason the models exhibit large component concentration discrepancies and uncertainties in model comparison studies (Kinne et al. 2003). Air pollution networks favor urban sites and, thus, are not well distributed for aerosol climatology. Critical chemical sampling needs include aerosol measurements aloft, assessments of how well point measurements at surface stations represent the surrounding regions, size-segregated chemical measurements for coarse and fine aerosol modes, and sample accumulation times shorter than the current 24-h standard.

LIDAR NETWORKS. Ground-based lidar networks contribute significantly to global aerosol monitoring (e.g., Welton et al. 2001; Murayama et al. 2001; Hoff and McCann 2002; Bosenberg et al. 2002; Matthias et al. 2004). Having high vertical and high temporal resolution, lidar can detect geometrically thin, elevated aerosol layers. Detailed altitude knowledge is helpful for assessing the radiative impact and for tracing particles back to their origins. Without sufficient vertical resolution, thin aerosol layers aloft can be masked by relatively thick boundary-layer aerosol. These elevated layers are important to cloud formation and long-range transport. Even though most aerosols reside in the boundary layer, on average, 80% of continental stations in Europe see elevated layers, which are impossible to separate from near-surface layers using sunphotometer measurements alone. Disadvantages of ground-based lidar include instrument complexity, a relatively high maintenance cost, difficulty in obtaining quantitative extinction coefficient calibration, and a lack of horizontal coverage. Even scanning lidars cover just a few kilometers, and a single station can produce only a two-dimensional cut in the four-dimensional observation space. This can be remedied to some extent with regional lidar networks.

Aerosol information from lidar ranges from a purely geometrical layer distribution with simple backscatter approaches to a comprehensive optical and microphysical characterization, using sophisticated multiwavelength systems that have separate channels for elastic backscatter, Raman backscatter, and depolarization. The advanced systems can characterize aerosol optical and microphysical properties in elevated layers, and can detect thin cirrus with fewer and less stringent assumptions than can other remote-sensing methods. Ground-based advanced lidars can improve the interpretation of data from simpler space-based lidars. Only a few systems are capable of such multiparameter retrievals, but the methods have been demonstrated, and many others are not far from the same level of sophistication.

Continuous or semicontinuous lidar observations also provide good temporal coverage at resolutions from minutes to years. In principle, ground-based systems can run day and night in a wide range of weather. Only precipitation, fog, and very low clouds prohibit useful operation. Generally, profiles extend only up to the base of the lowest optically thick clouds, but many cloud decks have at least some holes through which lidars can obtain profiles beyond the lower cloud layer. Even in regions considered unfavorable for lidar operation, successful observations are achieved a large fraction of the time (Bösenberg et al. 2001).

The Micropulse Lidar Network (MPLNET) (Welton et al. 2001) is a NASA-supported network of comparatively low-cost micropulse backscatter lidars, sited mostly in combination with sunphotometers, and coordinated with the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program. MPLNET has demonstrated that such lidars can be run continuously and autonomously. The Asian Dust Network (AD-NET) in east Asia observes dust outbreaks from the Gobi and adjacent deserts (Murayama et al. 2001). The European Aerosol Research Lidar Network (EARLINET), the largest network of advanced aerosol lidars, included 22 stations in 13 European countries at its peak, covering a major part of the continent (Bösenberg et al. 2002; Matthias et al. 2004). EARLINET showed that optical properties can be retrieved routinely; a few EARLINET partners even developed and successfully applied aerosol microphysical property retrievals. Quality-assurance techniques were also developed successfully, along with suitable data structures. A new network, the Commonwealth of Independent States Lidar Network (CIS-LINET), will be installed in the area of the former Soviet Union.

AIRCRAFT. Although assimilation can force agreement between model predictions and remote-sensing observations, only sampling within the atmosphere can assure that this occurs for the right reasons. The combination of satellite- and ground-based remote sensing described above are adequate to establish confidence in CTM calculations of aerosol optical depth, species concentrations at the surface, and aerosol backscattering and extinction vertical profiles. However, size-resolved aerosol absorption and chemical species concentrations above the surface, where much long-range transport occurs, are poorly constrained by these measurements. Such inputs are needed for process studies aimed at aerosol evolution and the indirect effects of aerosols on clouds, as well as for model validation. The ability of airborne instruments to characterize aerosols in the free troposphere has been demonstrated repeatedly (e.g., Russell et al. 2002; Clarke and Kapustin 2002; Clarke et al. 2002; Moore et al. 2003; and many others). Instruments ranging from sunphotometers and lidars to wet and dry nephelometers, absorption photometers, particle sizers and counters, ionization mass spectrometers, and sample collectors have been flown successfully in coordinated multiaircraft experiments. Advanced inlets have been developed to minimize sampling bias during in-flight particle collection (e.g., Lafleur 1998). But, to date, only episodic aerosol data have been collected by advanced airborne instruments.

A sustained program of aircraft measurements, integrated with surface- and space-based remote-sensing observations, would fill the enormous gap in aerosol property observations aloft. Cost is an issue, but a relatively inexpensive operational vertical profiling program, using light aircraft, has been demonstrated by the DOE (Andrews et al. 2004). In addition to aerosol microphysical properties, such profiling reveals the concentrations of aerosol that act as ice nuclei and can assist in verifying the methods used to retrieve cloud microphysical properties from remote-sensing measurements (e.g., Feingold et al. 2003; Andrews et al. 2004). Aerosol indirect effect studies would demand a more comprehensive suite of measurements, including CCN, cloud droplet size distribution, liquid water content, and updraft velocity measurements, requiring the use of midsized aircraft, such as a Twin Otter or Cessna Caravan.

Accordingly, selected ground stations could be augmented with light aircraft, measuring vertical profiles of aerosol properties. Priority should be given to regions having high anthropogenic emissions and other important regional aerosol effects and, for remote sensing validation, open ocean. Such profiling could target, for example, aerosol layers in the western Atlantic, dominated by North American pollution sources in some seasons, or aerosols over the western Pacific off east Asia, which contain both dust and wildfire smoke that can affect the entire Pacific basin in the spring. Model predictions of aerosol forcing sensitivity to the aerosol vertical distribution would aid in the choice of stations.

SHIPS. Despite the importance of sampling midocean areas downwind of continental plumes, as well as remote areas that can help to validate satellite retrievals, making routine measurements of optical properties from ships at sea is challenging. Optical instrumentation is vulnerable to salt deposition, spray, platform motion, stack gas, and precipitation. Nonetheless, shipboard measurements are required to develop a truly global surface measurement network. The Shipboard Oceanographic and Atmospheric Radiation (SOAR) program attempted to meet this need with a global network of research and volunteer ships carrying global-change instrumentation. The package included the Fast Rotating Shadowband Radiometer (FRSR) (Reynolds et al. 2001), capable of making direct and diffuse solar measurements from a moving ship. SOAR bundled supporting instrumentation into its installations, including a high-resolution meteorological package, ceilometers, and all-sky cameras. During its four years, SOAR amassed aerosol optical depth and other environmental data from over 150 cruises (Fargion and McClain 2003). A few parts of the SOAR capability are now supported by the ARM program and the University of Miami.

The University of Miami Rosentiel School of Marine and Atmospheric Science has operated SOAR instrumentation in conjunction with its Marine–Atmospheric Emitted Radiation Interferometer (M-AERI) instrument, a shipboard Fourier transform infrared radiometer (Minnett et al. 2001). M-AERI radiance spectra can be inverted to retrieve water vapor and temperature profiles for the lowest 3 km of the atmosphere (Feltz et al. 1998), and the infrared spectra have been used to observationally determine longwave aerosol forcing at the surface (Vogelmann et al. 2003). An impressive record of column-averaged aerosol optical properties, along with detailed chemical analyses of boundary-layer aerosols that could contribute to the global aerosol climatological picture, has also been collected by NOAA during research cruises (Quinn and Bates 2004, manuscript submitted to *J. Geophys. Res.*).

Routine measurements of aerosol optical thickness, cloud optical thickness, and diffuse irradiance can be made by ships that travel frequently through remote waters. Uncertainties in current surface-based aerosol optical-thickness measurements over the ocean are only slightly larger than uncertainties in land-based measurements, and could be reduced by using newly available technology (Miller et al. 2004). Aerosol radiative properties can be retrieved, and specific aerosol models that are used in satellite retrievals can be tested, with the help of radiometers that separate incoming solar radiation into its direct and diffuse components, as is done on land (Vogelmann et al. 2003; Miller et al. 2003; Knoblespiesse et al. 2004, manuscript submitted to *Remote Sens. Environ.*).

INTENSIVE FIELD CAMPAIGNS. Intensive field campaigns are usually designed to produce as complete an environmental characterization as resources allow. These campaigns usually support satellite and model validation, as well as detailed process studies. Recent targets have included pristine aerosol environments (e.g., Clarke and Kapustin 2002), biomass-burning areas (e.g., Haywood et al. 2003; Andreae et al. 2004), locations influenced by airborne desert dust (e.g., Russell and Heintzenberg 2000; Reid et al. 2003; Kahn et al. 2004), and regions heavily impacted by anthropogenic aerosol emissions (Russell et al. 1999, 2002; Clarke et al. 2002; Satheesh et al. 2002; Magi et al. 2004; and many others).

Campaigns need favorable meteorological conditions during limited field-operating periods. Those focused on direct radiative forcing typically require cloud-free areas, whereas studies of indirect forcing may require specific cloud conditions. Strategies for coordinating aircraft, surface station, and satellite observations for atmospheric column characterization have advanced immensely (e.g., Huebert et al. 2004; Russell et al. 1999, 2002; Russell and Heintzenberg 2000), but data-taking approaches could be refined further, especially for spatial heterogeneity and aerosol indirect-effect studies. Efforts to apply modern statistical methods to the analysis of the resulting multiplatform data are in their infancy.

INTEGRATED OBSERVING FACILITIES ("SUPERSITES"). To collect statistically representative datasets related to aerosol forcing of climate, the key measurement components of intensive field studies need to be deployed at facilities that operate continuously for years. Such integrated observing facilities, or "supersites," having a great variety of instruments, are slowly taking form around the globe. Supersites aimed at studying aerosol direct radiative forcing must include sunphotometers and radiometers for determining the surface radiation budget, plus in situ aerosol chemical, microphysical, and radiative instrumentation. Between 10 and 20 sites around the globe operate this basic integrated suite of instruments, and more are under development. A few sites also operate lidars.

A second class of supersites also has millimeter-wavelength radar and microwave radiometers for studies of aerosol indirect forcing. The first of these supersites was developed under the DOE ARM program (Ackerman and Stokes 2003); they are now being joined by others in Europe and at Darwin, Australia. A site in Japan or China may become operational in the future. Some very interesting studies of the linkages between aerosol concentration and cloud microphysical properties are beginning to emerge from the data collected (e.g., Feingold et al. 2003). However, none of the supersites currently supports a full complement of instruments needed to characterize aerosol indirect forcing. In particular, they lack coordinated, routine chemical and CCN measurements needed to link changes in aerosol properties to those in cloud properties. The situation is likely to improve quickly, in response to increasing interest in aerosol indirect effects.

Supersites currently provide only limited information about aerosols aloft. The ARM Southern Great Plains site has initiated twice-weekly profiles of aerosol absorption and scattering from a light airplane. Aircraft carrying additional samplers for aerosol hygroscopic growth, size distribution, and chemical composition, are needed at supersites to obtain aerosol properties that link remote-sensing measurements with CTM predictions. NOAA is developing such a system for deployment at a U.S. supersite in 2005.

CHEMICAL TRANSPORT MODELS. Three-dimensional aerosol CTMs are the best available means to compute global annually averaged anthropogenic aerosol radiative forcing (Haywood and Boucher 2000). Such models can calculate the relative amounts of natural and anthropogenic aerosols from emissions inventories. Composition-dependent aerosol hygroscopic growth factors are either assumed or calculated from laboratory data, and are applied based upon relative humidities calculated within the model or obtained from external sources. Aerosol optical properties are obtained from separate optical models. Efforts are under way to compute the following within CTMs: 1) aerosol light scattering and absorption as a function of wavelength, particle size, scattering angle, and relative humidity; 2) aerosol number size distribution; 3) size-resolved aerosol chemical composition, including major ionic species, elemental and organic carbon, mineral dust, and total mass; 4) spectral aerosol optical depth; 5) particle shape distribution; and 6) the number concentration, size distribution, and chemical composition of CCN, as a function of supersaturation, all in three spatial dimensions at every time step. In practice, aerosol mass loading is usually the primary variable reported, and most modelers concentrate on the parameterizations of selected microphysical processes. Assumptions independent of the CTM itself are needed to derive aerosol optical properties, comparable to those observed in the field, from model-calculated aerosol mass loading.

In the context of PARAGON, the relationships between CTMs and measurements are of special interest. CTMs capable of assimilating satellite or field data can serve as physically based interpolation schemes, producing a global, four-dimensional aerosol picture constrained by observations. Places where CTMs show high sensitivity to local conditions would be prime candidates for new monitoring sites, to better constrain the models. Regions where assimilations require frequent, large adjustments to the modeled fields would point to situations where model parameterizations may need to be refined; such locations could also be candidates for additional observations.

CONCLUSIONS. A great number and variety of aerosol measurements are already being acquired, both routinely and as a result of occasional, intensive campaigns (see Table 2 for a summary of the strengths and limitations of various data sources). Available technology makes it possible to meet many of the measurement requirements of aerosol direct forcing (Seinfeld et al. 2004), though accuracy improvements are still needed for remote sensors. Gaps remain in the data that are actually obtained, and much intercomparison of existing data remains to be done.

Important gaps in available aerosol datasets include multiparameter climatologies at the surface, and vertical profiles of aerosol microphysical properties. Most long-term aerosol-observing programs provide either chemical or radiative properties, whereas both are needed to validate satellite retrievals and model-derived results. Only about a dozen monitoring stations around the globe routinely obtain the key variables that quantitatively link satellite observations with model predictions: radiative forcing efficiency, mass

Table 2. Attributes of various data sources.

Source	Strengths	Limitations
Satellites	Provide global retrievals of aerosol optical depth and properties such as size distribution and shape with frequent repeat coverage.	Retrievals are underdetermined. Chemical composition cannot be retrieved other than by coarse proxies.
Solar and sky radiometer networks	Measure aerosol optical depth and downwelling radiances directly, with high accuracy and frequent sampling. Provide estimates of aerosol size distribution, phase function, and single-scattering albedo.	Are poorly coordinated with in situ and active systems, limiting accuracy assessment and restricting results to clear-sky conditions. Only column-averaged properties are provided, and size-resolved single scattering albedo is not obtained.
Chemistry and microphysics networks	Provide direct particle and gas phase chemical abundance measurements.	Provide surface-sited point measurement only. Samples often average over periods longer than aerosol correlation times.
Lidar networks	Acquire data with high vertical resolution and high temporal resolution/coverage.	Have poor horizontal coverage; many regions are unsampled. Complex systems are needed to reduce indeterminacies associated with simple backscatter lidars.
Aircraft	Provide aerosol absorption and chemical species concentrations aloft, as well as cloud microphysical properties.	Have limited geographic and temporal coverage.
Ships	Provide midocean retrievals of aerosol optical depth and optical properties.	Oceans remain highly undersampled.
Intensive field campaigns	Involve aircraft, ships, and surface stations to provide detailed characterizations of aerosol physical, chemical, and optical properties.	Are complex to implement, have limited duration (order of weeks), and focus on few sites.
Integrated observing facilities (supersites)	Provide continuous measurements of aerosol, radiation, and cloud properties with active and passive techniques.	Have limited geographic coverage, high cost per site.
Chemical transport models	Compute a variety of aerosol and cloud microphysical and column parameters, along with radiative forcing estimates, with uniform and global sampling in space and time.	Inputs for process models (e.g., nucleation mechanism), average properties at the grid scale, and source inventories are often poorly known. Quality of forcing estimates are directly dependent on accuracies of inputs and assumptions.

scattering efficiency, single-scattering albedo, and hygroscopic growth characteristics of major aerosol types. Information about the vertical profiles of these parameters is even less common, currently limited to those collected during intensive field campaigns. Instrumented light airplanes, complemented by advanced lidars, offer the best approach for routine vertical profiles of these key aerosol properties. One of the greatest current instrument challenges appears to be developing techniques that can determine particle spectral single-scattering albedo to a few percent accuracy, critical for calculating aerosol forcing and measuring the relative humidity dependence of aerosol light-absorption coefficients.

A far more comprehensive picture of aerosol intensive and extensive properties could be achieved with an infrastructure that would make it easier to access and handle data from multiple sources. Serious work is also needed on statistical methods for integrating data having different spatial and temporal sampling characteristics. The companion paper by Ackerman et al. (2004) discusses these matters in detail.

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