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SATELLITE-BASED MEASUREMENT OF ATMOSPHERIC AEROSOLS

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30.1 INTRODUCTION

Radiation sensors on earth-orbiting satellites offer a way to observe atmospheric aerosols at about kilometer resolution, near real time over much of the globe. The aerosol back-scattering of solar radiation allows us to observe the pattern of atmospheric aerosols from major pollution events, dust storms, forest fires, and other aerosol events. In fact, the patches of bluish smoke-haze and yellow dust plumes are prominent features of the earth as viewed from space. Satellite aerosol measurements have also shown great potential to contribute to earth science, to the assessment of air quality, and to the management of some disasters. Global-scale aerosol monitoring has the further potential to improve our understanding of aerosol-induced climate effects. Thus, it is expected that satellite aerosol observing and measuring systems will continue to expand their utility.

Unfortunately, the quantitative measurement of aerosol properties has proven to be a challenge since the beginning of the satellite era in the 1960s. This is no surprise, since satellite-based measurement is among the most complex aerosol measuring techniques. In principle, atmospheric aerosols are well suited for satellite remote sensing. The sun provides a stable light source, the aerosol scattering covers the entire solar spectrum, and the radiation is easily detectable by high resolution sensors. The difficulties for quantitative aerosol measurements include: (1) Aerosol scattering is just one of the four components of the detectable radiation (Fig. 30-1a) and separation of the weak aerosol signal from the other signal components is error-prone; (2) Associating the angular back-scattering by aerosols with intrinsic aerosol properties is burdened with ambiguity; and (3) The downward-looking satellite sensors measure the total back-scattering, which is the integral over the entire atmospheric column.

This chapter is a brief summary of satellite aerosol detection and measurement. The chapter begins with a background on aerosol remote sensing followed by a summary of aerosol optical parameters relevant to satellite detection. The bulk of this chapter is devoted to the physical principles and the challenges of satellite aerosol detection. Following a section on satellite data dissemination, illustrative application examples are given for earth science and air quality management. The chapter is concluded with a list of desirable developments in satellite aerosol measurements. For more details, the reader is guided to the excellent textbooks on atmospheric aerosol measurement.
aerosols (Seinfeld and Pandis 1998; Friedlander 2000), the review of atmospheric aerosol measurements by McMurry (2000), and atmospheric visibility measurements and science by Watson (2002). For more details on satellite aerosol measurement systems see the authoritative article by King et al. (1999), the recent broad review by Hoff and Christopher (2009) and the comments by Hidy et al. (2009).

30.2 BACKGROUND ON SATELLITE REMOTE SENSING

Atmospheric aerosol characterization using optical techniques has a rich history, a vigorous present, and bright prospects for the future. The abundance of atmospheric optical data prompted early investigators to seek information about aerosol properties via the optical data. Following the Krakatoa eruption, Kiessling (1884) concluded that he volcanic dust with characteristic size between 1 and 2 \( \mu \text{m} \) caused the spectacular optical phenomena worldwide. Wegener (1911) used a simple but most elegant reasoning to infer that the characteristic size of the atmospheric haze particles is comparable to the wavelength of visible light. With the advent of computers, numerical inversion procedures were developed to infer aerosol size distributions from optical, that is, spectral and angular aerosol-scattering measurements. For example, based on the inversion of spectral extinction data, Penndorf (1957) concluded that the peculiar blue sun and blue moon phenomena in Europe were due to aged Canadian forest fire smoke with the characteristic size of 0.6–0.8 \( \mu \text{m} \). Recently, a more sophisticated inversion scheme was offered by Dubovik and King (2000) for the

![Radiation components detected by a satellite aerosol sensor.](image)

![Polar and geostationary satellite orbits.](image)
30.3 AEROSOL PHYSICAL AND OPTICAL PROPERTIES

Aerosol data sets and climatologies are derived from polar orbiting satellites carrying a variety of sensors. The full characterization of an aerosol system requires eight orthogonal dimensions \((x, y, z, t, D, C, S, X)\). Satellite sensors have high spatial resolution \((x, y)\) but they detect the optical effect of a vertical column, which is an integral over five dimensions \((z, D, C, S, X)\). The de-convolution of this integral is a notoriously ill-posed mathematical problem that does not possess a unique solution. In other words, the
The number of unknown aerosol parameters is much larger than the known entities from optical measurements. This inversion problem is made extra uncertain by the fact that the aerosol optical signal at the top of the atmosphere is weak compared to the noise from the surface reflectance, interference from clouds, and from the complications of a meta-stable aerosol system.

A strategy toward the solution of the inversion problem is to reduce the dimensionality of the aerosol system. Such reduction can be achieved by observing the regularities of atmospheric aerosol behavior and applying those regularities to satellite aerosol measurements. The key aerosol microphysical parameters relevant to the optical detection of aerosols are shown in Figure 30-2a.

The aerosol volume (or mass) is typically distributed between the fine particle mode in the diameter range 0.1 μm to about 2 μm range and the coarse particle mode above 2 μm. In a nutshell, the model introduced by Whitby and co-workers (Whitby et al. 1972; Whitby 1978) states that each aerosol mode has a characteristic size distribution, chemical composition, and optical properties. More details on size distribution characteristics of atmospheric aerosols are presented in Chapter 4. The multi-modal concept has been widely adopted as the standard size distribution model by the aerosol remote-sensing community (Remer and Kaufman 1998; Kahn et al. 2001; Dubovik et al. 2002).

Fine mode particles (below 1–2 μm) are mostly formed by combustion and condensation processes, resulting in spherical liquid droplets that are frequently meta-stable. Hence, the size distribution and optical properties of fine particles is highly dynamic and responsive to environmental conditions such as gas particle conversion, relative humidity, and chemical interactions among particles. Over urban industrial regions the fine particle mode is composed of sulfate, organic, and nitrate species, each having somewhat different size distribution (Seinfeld and Pandis 1998). Fine particles tend to be internally mixed, but may exhibit multiple mass modes. Sulfate particles, for instance, occur in two distinctly different mass modes depending on whether the formation mechanism is photochemical gas particle conversion (mass mode ≈ 0.2 μm) or through liquid-phase reactions (mass mode ≈ 0.5 μm) (McMurry et al. 1996). Fine particles exhibit another regularity of increased mass median diameter with increasing concentration. This is significant because it allows the formulation of dynamic aerosol models that directly relate the spectral and angular scattering characteristics to aerosol concentration (Remer and Kaufman 1998; Dubovik and King 2000). Coarse-mode atmospheric particles tend to originate from primary emissions, for example, windblown dust, sea salt, fly-ash, and road dust, and they are irregular in shape. The radiative impact of coarse particle mixtures are additive. An exception to this rule is when ambient air is ingested into

\[ Q_{13} \]

Figure 30-2 Aerosol physical properties relevant to optical detection. (a) Aerosol mass distribution. (b) Light-scattering and absorption per unit aerosol volume (or mass). (c) Change in the phase function as a function of extinction coefficient.
cloud droplets and the result is internal mixing of all particles in the cloud droplets. Sea salt particles may also grow at high humidity.

The most critical aerosol optical property for satellite aerosol retrieval is the angular scattering since satellites detect the cumulative scattering of sunlight in the view-path of the sensor (Fig. 30-1a). The directional dependence of scattering is defined by the phase function \( P(\theta) \) which is the ratio of the energy scattered into direction, \( \theta \), to the average energy scattered into all directions. See Chapter 13 for detailed discussion on fundamentals of light scattering by aerosol particles. The scattering angle, \( \theta \), is the angle between the sun, the aerosol volume, and the sensor (Fig. 30-1a). Unlike the symmetric Rayleigh scattering by pure air, the scattering phase function for aerosols is elongated in the direction of the incoming light. Barteneva (1960), observed a remarkable dependency of the phase function shape on the aerosol extinction coefficient in the former Soviet Union. With increasing extinction coefficient, the “cigar”-shaped aerosol phase function becomes increasingly shifted toward the forward direction (Fig. 30-2c). This pattern is consistent with the notion that at higher extinction coefficients, the characteristic particle size increases and the scattering is more and more forward directed. The broader applicability of Barteneva’s observations was confirmed through airborne polar nephelometer measurements in the United States by Johnson (1981). However, the nature of the phase function varies considerably (Sakunov et al. 1996). A pixel-level comparison of aerosol optical depths (AODs) derived from MODIS and MISR satellite aerosol instruments sensors found a significant deviation as a function of the scattering angle between the two satellite aerosol measuring systems (Mishchenko et al. 2009). This further highlights the need for increased attention to the aerosol phase function.

Another feature of atmospheric aerosols is that at any given region, there is a high correlation between the total light-scattering coefficient and the mass concentration of fine particles, below 2.5 \( \mu \text{m} \) in size. The slope of the correlation corresponds to scattering efficiency, \( \alpha \approx 3–5 \text{ m}^2/\text{g} \) (Malm and Hand 2007), which is generally applicable for sulfates, nitrates, and organics in the fine particle mode with a peak in extinction efficiency in the 0.3–0.8 \( \mu \text{m} \) size range (Fig. 30-2b). For atmospheric dust particles, the corresponding extinction efficiency per unit mass is much less (\( \alpha \approx 0.6 \text{ m}^2/\text{g} \)), as documented by White (1986). The observed regularity and ubiquity of this relationship allows the estimation of fine particle columnar mass concentration \( M_{fc}[\text{g/m}^2] \) from measured optical thickness, \( \tau \) through \( M_{fc} = \tau/\alpha \).

The vertical layering of the atmospheric aerosols also requires special consideration. It is known that aerosols tend to reside in distinct layers of the atmosphere, as illustrated schematically in Figure 30-3. The vertical distribution can be subdivided into three layers, each layer having different aerosol types, atmospheric residence time, and mixing characteristics. The stratospheric or Junge layer (Fig. 30-3a) is composed primarily of volcanic sulfuric acid aerosols that circle the earth at 10–15 km elevation for a year or two after volcanic eruptions. Below the stratosphere is the tropospheric layer, which is the carrier of dust, smoke, or occasional industrial haze ejected from the boundary layer. Tropospheric aerosols are thin pancake-like layers that may cover 1000-km size areas and tend to circle the earth during their 1–2 week residence time. The individual layers of tropospheric dust, smoke, and haze do not interact, hence their optical effects are additive. The bottom layer is the planetary boundary layer (PBL) that contains a large variety of aerosols from anthropogenic and natural sources (Fig. 30-3). Precipitation and other removal mechanisms

Figure 30-3 (a) Schematic representation of the aerosol vertical distribution. (b) Astronaut photo of stratospheric aerosol layers. (c) Complex physical and radiative interaction between aerosols and clouds.
restrict the aerosol residence time in the PBL to 3–5 days. Each aerosol type has its own sources and transport and optical characteristics and therefore deserves to be treated separately with specific aerosol physical and optical parameterization. In Figure 30-3a, the aerosol types that are in separate boxes are externally mixed and their respective radiative effects are additive. A group of aerosol types in the boundary layer that are in adjacent boxes represent aerosol types that are generally internally mixed and their physical, chemical, and optical properties and behaviors need to be considered jointly.

The above discussion is a simplified description of the characteristics of atmospheric aerosols. A challenge of satellite aerosol measurements is to clearly delineate which aspects of aerosol characterization can be supported by satellite sensors and their retrieval algorithms.

30.4 PRINCIPLES OF SATELLITE AEROSOL DETECTION AND MEASUREMENTS

The science of satellite aerosol measurements is based on well-understood fundamental physical principles: Mie theory of light scattering and the theory of radiative energy transfer through scattering and absorbing media. The very same physical laws that govern satellite aerosol detection are applied to atmospheric visibility studies. In fact, satellite aerosol detection and daytime vision by the human eye operate on the same general principle of passive remote sensing (Fig. 30-1a): The radiation source is the sun; the target is the earth’s surface; the detector is an array of color-sensitive sensors, that may be the retina in the human eye or the satellite radiation sensor. In between the reflecting surface and the light sensor is the radiatively active atmosphere consisting of aerosols, air, and clouds. However, the two fields have different objectives and evolved rather independently from each other. The objective of visibility studies is to measure and model the ambient aerosol microphysics and chemistry and to evaluate the resulting effects on the optical environment. Satellite aerosol remote sensing on the other hand intends to solve the much more difficult inverse problem of deriving the properties of atmospheric aerosols from the measured optical effects at the top of the atmosphere. The inherent problem is that the retrieval of the unknown aerosol properties requires knowledge of those same properties. The current practice for resolving the inversion paradox is to prepare a discrete set of “aerosol models,” and to choose the model that best fits the satellite optical data in the form of spectral or angular scattering. The aerosol models and the surface reflectance models are typically tailored to the characteristics of the particular sensor.

The radiative signal received by a satellite is the combined contribution of surface reflectance and aerosol reflectance. For the sake of illustration, a single-scatter radiative transfer theory is used here to show the aerosol interactions with solar radiation. The separation of the aerosol signal from the surface reflectance can be achieved by the solution of the appropriate radiation transfer equation as derived in (Husar and White 1976). The resulting relationship between the surface reflectance and aerosol optical parameters is shown in Figure 30-4.

The aerosol perturbation of the upwelling radiation consists of two competing effects. On one hand, light-scattering particles tend to add reflectance to bright surfaces. This excess reflectance depends both on the aerosol optical thickness, \( \tau \), as well as the aerosol scattering phase function, \( P \). The other role of aerosols is to act as a filter that exponentially diminishes the upwelling radiation from a reflecting surface and from aerosol scattering itself. The net result of these two competing aerosol effects is illustrated in Figure 30-5d, where the apparent reflectance is plotted against the aerosol optical thickness. The bundle of curves corresponds to different values of surface reflectance \( R_0 \). The simplest case is when the surface is black, \( R_0 = 0 \) and the received radiation is purely due to aerosol scattering along the path, that is, the path radiance \( PR = (1 - e^{-\tau})P \) (Kaufman 1993). For an optically thin aerosol layer, \( \tau < 1 \), \( PR \) is proportional to the optical thickness, since self-extinction of the aerosol layer is minimal. As the aerosol layer approaches \( \tau > 2 \), self-extinction becomes more significant and by \( \tau > 4 \), the apparent reflectance asymptotically approaches the value of \( P \), which is the case for radiative equilibrium. Good examples for the strong path radiance are dark surfaces such as ocean or vegetation at blue wavelength where \( R_0 \) is small (<0.05), compared to \( P \approx 0.3 \) (Fig. 30-5b,c).

The opposite case occurs when the surface reflectance \( R_0 \) is high compared to \( P \). In this case, the addition of aerosol optical thickness actually diminishes the initial high surface reflectance, since the filter term dominates over the aerosol reflectance term. As the aerosol layer above the bright surface becomes optically thick, \( \tau > 4 \), the apparent reflectance asymptotically approaches the value of aerosol reflectance, \( P \). For example, an aerosol layer on top of bright clouds will tend to decrease the brightness of clouds. Figure 30-5a

![Figure 30-4 Illustrative radiative model for aerosol remote sensing.](image-url)
is an example of a layer of yellow dust on top of white clouds reducing the cloud reflectance. The next interesting case is when the aerosol phase function has the same value as the surface reflectance function, $P = R_0$, in the direction of sensor’s line of sight. In this case, adding aerosol will not change the apparent reflectance. At $P \approx R_0$ (e.g., soil and vegetation at 0.8 $\mu$m), the reflectance is unchanged by typical haze aerosols and aerosol detection is not possible.

The critical measure, whether aerosol will increase or decrease the apparent reflectance, is the ratio of the aerosol and surface reflectances, $P/R_0$. Figure 30-5d also shows that with increasing aerosol optical thickness the apparent reflectance of bright and dark surfaces converge toward the value of the aerosol scattering function, $P$. In other words, with increasing AOT, the contrast between dark and bright surfaces diminishes and they become indistinguishable as $\tau$ exceeds 4. In the case of an optically thick aerosol layer, the filtering and scattering effects of aerosols are balanced, that is, the aerosol system reaches radiative equilibrium. The implication is that the retrieval of $\tau$ for optically thick aerosol layers ($\tau > 4$) is not possible. Aerosol retrieval is also limited when $P \approx R_0$, which occurs over the bright surfaces of deserts and rocky terrains.

![Figure 30-5](image_url)

**Figure 30-5** (a) Spectral reflectance with and without aerosol clouds. (b) Vegetation. (c) Ocean. (d) Apparent surface reflectance as a function of $P/R_0$ and AOT.
are related by the following simple expression, \( \tau = \ln(R - P)/(R_0 - P) \). The value of \( P \) is obtained from fitting the observed and retrieved surface reflectance spectra. For example, in light haze at 412 nm, it is found that \( P = 0.38 \).

The color Figure 30-6 provides a graphic illustration of the key steps in satellite aerosol retrieval. The hazy SeaWiFS image (Fig. 30-6a) shows the composite signal received by the sensor on July 16, 2009. The image was synthesized from the blue (0.412 \( \mu \)m), green (0.555 \( \mu \)m), and red (0.67 \( \mu \)m) channels. The aerosol-free surface reflectance (Fig. 30-6b) was derived from time series data. The aerosol optical depth (Fig. 30-6c) was calculated from the excess radiance, that is, the difference between the hazy and haze-free reflectances at the blue (412 nm) wavelength. The resulting aerosol pattern shows qualitatively the hazy patches (red) over the ocean as well as in the vicinity of cloud systems. The black areas are blocked out by the cloud mask.

Figures 30-6a,b,c show the received signal at three wavelengths. At blue wavelength (412 nm) Figure 30-6d, the apparent reflectance, \( R \), reaching the satellite sensor is dominated by the haze since the surface reflectance is low over the ocean and vegetation. The aerosol patterns are clearly discernible, while all the surface features are obscured by haze. Hence, the blue wavelength is well suited for aerosol detection over land (Hsu et al. 2006) but surface characterization is difficult (see Fig. 30-5c). At red wavelength (670 nm), Figure 30-6e, the apparent reflectance is contributed to significantly by both surface reflectance and aerosol reflectance. However, the magnitude of the surface reflectance differs greatly for vegetated and solid surfaces, such as urban centers. Hence, at the red wavelength aerosol detection over land is difficult because it is very sensitive to the type of underlying surfaces. Over the ocean the aerosol reflectance is high compared to the water reflectance, and therefore...

**Figure 30-6** (a) True-color composite of SeaWiFS satellite data for July 15, 1999. (b) Surface reflectance in the absence of aerosols and clouds. (c) Derived aerosol optical depth, AOD. (d–f) Measured apparent reflectance at 412-, 670-, and 870-nm wavelength, respectively, showing increasing atmospheric transparency at higher wavelengths. (See color insert.)
quantitative aerosol detection is possible. The near-IR wavelength (865 nm), Figure 30-6f, is uniquely suitable for aerosol detection over the ocean since the ocean reflectance is below 1%. Hence, virtually all the apparent reflectance is due to aerosol scattering. Over land, the reflectance of both vegetated and solid surfaces is high and comparable to the aerosol reflectance $P$, that is, $P/R_0 \sim 1$ and aerosol detection is limited.

### 30.5 CHALLENGES OF SATELLITE AEROSOL MEASURING SYSTEMS

Practical satellite aerosol measurements face a number of additional challenges beyond the dynamic and multidimensional aerosol system. Clouds obscure the detection of both underlying surfaces and atmospheric aerosols. The areas delineated by a “cloud mask” are unavailable for aerosol detection. Since large portions of the tropics and northern latitudes are cloudy throughout the year, cloudiness is a major limitation of satellite remote sensing of both aerosols and surfaces. The cloud edges are not easily discernible, particularly during humid conditions and hygroscopic (e.g., sulfate) haze. Thin cirrus clouds are also difficult to identify. Consequently, improper cloud masks are a source of error in satellite-derived aerosol measurements. Cloud shadows on the earth’s surface also constitute a complication for aerosol retrieval.

Air or Rayleigh scattering of blue light always contributes to the radiation detected by the satellite sensor. The magnitude of air scattering can be corrected by rigorous calculations based on the known optical properties of air molecules, the elevation of the surfaces, and by application of well-established radiative transfer code, such as that offered by Vermote et al. (2002). Absorption by stratospheric ozone and tropospheric water vapor also attenuates selected bands in the solar spectrum passing through the atmosphere. The stratospheric ozone layer has an interfering absorption band in the visible range (0.52–0.74 μm). Whenever possible, the satellite sensor wavelength bands are located in transmission windows, that is, at wavelengths away from major molecular absorption bands.

From the perspective of aerosol detection, the highly textured and colorful reflection from the earth’s surface constitutes a significant background noise that needs to be dealt with. The surface reflectance, that is, the fraction of the incoming solar radiation reflected by a surface, depends on many parameters most notably on the nature of the surface itself and the geometric and spectral distribution of incoming and reflected radiation. Ocean surfaces reflect the incoming radiation, mostly by mirror-like, specular reflection. The areas of “sun glint” can be identified from the sun-surface-sensor geometry and can be masked out just like clouds (Khan et al. 2007). Ocean waves tend to broaden the angular spread of the specular reflection and may also add spurious reflectance from foaming whitecaps. Solid land surfaces are mostly diffuse Lambertian reflectors, with minor specular components. Vegetation is a nearly diffuse Lambertian reflector but exhibits an extra reflection “hot spot” back toward the sun. Over land, the surface reflection is defined by the bidirectional diffuse reflectance function (BDRF; Roujean et al. 1992). It depends on the angle of the incoming radiation and the angle of reflected radiation as well as on wavelength. Vegetation reflectance has a peak in the green (0.5 μm) and rises sharply to over 40% in the near IR. Typical soil or rock reflectance gradually increases from about 10–15% in the blue to over 40% in the near IR. The spectral reflectance of water is low in the visible range and vanishes in the near IR, making it practically black. The spectral reflectance of many surfaces varies with season. Unfortunately, the a priori quantification of the spectral BDRF is not available for the ever-changing earth surfaces at all locations and all times. This necessitates the extraction of key features of BDRFs from the “dirty” satellite images using spectral reflectance values for the same pixel on different observation conditions (e.g., Raffuse 2003).

The performance of satellite aerosol sensors and their respective retrieval algorithms are evaluated primarily against observations of optical thickness data provided by the AERONET (Holben et al. 1998) sun photometer network. This federated network has strategically located sites that characterize typical aerosol regimes such as dusty desert locations, biomass smoke areas, marine background, as well as urban industrial sites with complex aerosol mixtures. The validation results appear to confirm the anticipated retrieval accuracy of MODIS and MISR products (Abdou et al. 2005; Kahn et al. 2005, 2007; Remer et al. 2008). However, a direct comparison of MODIS and MISR aerosol data show significant disagreements at the pixel level as well as between long-term and spatially averaged aerosol properties, particularly over land (Liu and Mishchenko 2008).

### 30.6 SATELLITE DATA AND INFORMATION SYSTEMS

Earth observing satellites are by far the most prolific sources of environmental monitoring data. Literally terabytes of digital data are collected, transmitted, and processed daily. An integral part of earth observing satellite systems is the data flow and processing network, that is, the information system that distributes the relevant processed data to the end users. Virtually all the raw and processed satellite products are publicly accessible from their respective agencies. NASA, NOAA, and other agencies have a rich variety of data products relevant to atmospheric aerosols. In fact, atmospheric particulate matter, that is, dust, smoke, and
haze are represented prominently (about 15%) in the NASA product showcases, like the Earth Observatory. Most of these aerosol products are images from the MODIS sensor on the TERRA and AQUA satellites. Other relevant data include AERONET federated sun photometer data, space LIDAR data from the PICASSO active LIDAR sensor, and the OMI data from the joint NASA-European Space Agency program.

Recent developments in surface and satellite sensing along with new information technologies now allow real-time, “just-in-time” data analysis for the characterization and partial explanation of major air pollution events as well as more in-depth postanalysis (Husar and Poirot 2005). However, for the users of satellite data, the new developments introduced a new set of problems. The “data deluge” problem is especially acute for analysts interested in aerosol pollution, since the aerosol processes are inherently complex, the numerous relevant data range from detailed surface-based chemical measurements to extensive satellite remote sensing and the integration of these requires the use of sophisticated data integration and modeling science methods. Unfortunately, neither the current science nor the tools and methods are adequate for such sophisticated data integration. As a consequence satellite-derived earth observations are severely underutilized in making societal decisions. A remedy is anticipated from the Global Earth Observation System of Systems (GEOSS), (GEOSS 2005) an emerging public information infrastructure for finding, accessing, and applying diverse earth observations that are useful for science and decision makers.

30.7 APPLICATIONS

There is increasing demand for satellite aerosol measurements in earth science, air quality management, and disaster management. Satellite-derived global aerosol climatologies have improved our general understanding of global biogeochemical processes of sulfur, organics, mineral dust, and other substances that are vital to the earth system. Vertical aerosol column observations are key to the characterization of the atmospheric aerosols, since most of the aerosol mass as well as the atmospheric processes occur aloft. Surface-based measurements characterize only a thin horizontal aerosol layer. Satellite observations made it possible to identify and derive global-scale aerosol source regions (e.g., Prospero et al. 2002), global-scale transport patterns (e.g., Husar et al. 1997), and also crude estimates of atmospheric aerosol residence times. These observation-based emission rates and atmospheric residence times, in turn, are improving the performance of global and regional chemical transport and forecast models.

With increasing concern about human-induced climate change, quantitative global-scale monitoring of radiatively active atmospheric aerosols has become a major goal. While aerosol back-scattering to space tends to reduce the incoming solar radiation, aerosol absorption contributes to the heating of the atmosphere. However, the magnitude of these perturbations and the relative contribution of the human-induced aerosol burden to heating and cooling effects is not well understood. Unfortunately, the current satellite-derived aerosol measurements are too uncertain to authoritatively resolve these subtle aerosol effects (Mishchenko et al. 2009).

Air quality management is a recent application area of satellite aerosol measurements. In the past, air quality regulations for aerosols relied on surface-based monitoring networks to enforce the air quality standards. More recently the U.S. Environmental Protection Agency’s (USEPA) Exceptional Event (EE) Rule (Federal Register 2008) explicitly encourages the use of satellites for the documentation of aerosol contributions that originate outside the jurisdiction of air quality control agencies. In fact, compelling satellite observations of smoke and dust events prompted the introduction of the EE Rule. Figure 30-7 is an example of an exceptional smoke event where biomass smoke from forest and agricultural fires in southern Mexico and Guatemala was transported across the entire eastern United States and caused record surface aerosol concentrations through most of the transport path. The spatial pattern of the bluish smoke plume and white clouds for May 15–16, 1998, was derived from the SeaWiFS satellite data. The semiquantitative absorbing aerosol index measured by the TOMS satellite sensor (green overlay) indicates that the aerosol is light-absorbing smoke, not sulfate haze. The aerosol extinction coefficient (red contour lines), derived from surface visibility observations, indicates that the smoke was reaching the ground and impacts human health. Such combination of multi-sensory satellite observations along with surface monitoring data and diagnostic transport models provides the evidence that the pollution event was due to uncontrollable, extra-jurisdictional causes and not from urban-industrial sources. Similar integration of satellite and surface observations and models have elucidated the intercontinental transport of windblown dust from the East Asian Gobi Desert and its impact on the west coast of North America (Husar et al. 2001).

Satellite aerosol observations are expected to continue to contribute to several aspects of air quality management, including: (1) providing direct observational evidence of regional and long-range aerosol transport; (2) helping improve emission inventories and tracking emission trends; (3) evaluating air quality models; and (4) complementing surface networks through filling of spatial-temporal gaps. However, before satellite aerosol observations can reach the “promised land” (Hoff and Christopher 2009), it will be necessary to better understand their measurement limitations (Hidy et al. 2009) and to develop science-based
methods of integrating satellite data with surface observations, emission inventories, and chemical transport models (NRC 2010).

### 30.8 FUTURE DEVELOPMENTS

Quantitative satellite measurements of aerosol properties are constrained by inherent physical and mathematical limitations. However, both the scientific understanding and the tools and methods of satellite aerosol sensing are maturing. Therefore, it may be appropriate to express desirable developments as perceived by this writer and the need for more interdisciplinary collaboration. Much of the knowledge on “aerosol models,” including aerosol size distribution dynamics, chemical composition, and optical properties, has been generated through atmospheric aerosol and visibility research and is directly applicable to the improvement of satellite aerosol detection. Conversely, satellite aerosol monitoring can significantly enhance the understanding of atmospheric aerosols, including emissions, transport, and spatio-temporal patterns. Thus, dynamic models for different aerosol types could be co-developed by aerosol scientists and remote-sensing specialists. More robust and continually updated surface reflectance models could help aerosol retrieval as well as surface characterization. Iterative co-retrieval of aerosol and surface properties could be one possible approach.

Future aerosol retrievals could utilize complementary and redundant information from multiple sensors, that is, through pixel-level fusion of multiple sensors’ data. Feature-level data fusion, for example, TOMS/OMI data with MODIS/MISR, could strengthen aerosol type detection. Fusion of geostationary and polar satellite data could yield a better characterization of aerosol dynamics throughout the day. An opportunity for the integration of multiple sensors is being pursued by the “A-Train,” a synchronized constellation of eight satellites that fly on near-identical orbits as a pack (Stephens et al. 2002).

A more difficult issue is: What comprehensive, integrated system is needed for improving air quality management using satellite and ground-based observations along with evolving modeling and emission inventories (Hidy et al. 2009). Lastly, the concept of “aerosol retrieval” could well be expanded beyond the explicit use of the optical aerosol signal processing arising from single instruments. A more complete effort that is directed toward the full characterization of the entire eight-dimensional aerosol system could produce dramatic improvements in our understanding and also provide benefits to many application areas, such as air quality and human health, climate change, and disaster management.
Q4 30.9 ACKNOWLEDGMENTS

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30.10 LIST OF ACRONYMS

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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AERONET</td>
<td>Aerosol robotic network</td>
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<td>AOD</td>
<td>Aerosol optical depth</td>
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<td>AQUA</td>
<td>Earth-observing NASA satellite</td>
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<td>AVHRR</td>
<td>Advanced very high resolution radiometer</td>
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<td>BDRF</td>
<td>Bidirectional diffuse reflectance function</td>
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<td>USEPA</td>
<td>U.S. Environmental Protection Agency</td>
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<td>GEOSS</td>
<td>Global Earth Observation System of Systems</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>MODIS</td>
<td>Moderate resolution imaging spectroradiometer</td>
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<td>MISR</td>
<td>Multiangle imaging spectroradiometer</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space administration</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>OMI</td>
<td>Ozone monitoring instrument</td>
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<td>PICASSO</td>
<td>Pathfinder instrument for cloud and aerosol spaceborne observations</td>
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<tr>
<td>TERRA</td>
<td>Earth-observing NASA satellite</td>
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<tr>
<td>TOMS</td>
<td>Total ozone mapping spectrometer</td>
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<tr>
<td>SeaWiFS</td>
<td>Sea-viewing wide field-of-view sensor</td>
</tr>
</tbody>
</table>

30.11 REFERENCES


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