

Satellite Remote Sensing: Aerosol Measurements

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Dedication: This article is dedicated to the memory of Dr. Yoram J. Kaufman, who co-authored the entry for “Satellite Remote Sensing: Aerosol Measurements” in the previous edition of this Encyclopedia. Yoram’s many creative ideas greatly enriched this field, and his untimely passing in June 2006 was a great loss to our community.

50-100 word synopsis

Because aerosols vary on many spatial and temporal scales and exhibit a diversity of environmental impacts, satellite remote sensing makes an essential contribution to the study of airborne particles. Since the very first orbiting imagers began observing Earth, the scope of satellite data products has provided inspiration, qualitative indications, and increasingly, quantitative constraints on the regional and global influences aerosols exert. Major advances in this field have taken place in the last decade, providing better constraints on atmospheric processes, short-term forecasting, and climate modeling. Further advances can be expected from greater integration of satellite and suborbital data with models.

Main body

Satellite Remote Sensing: Aerosol Measurements

Introduction

Aerosols are solid or liquid particles suspended in the air, and those observed by satellite remote sensing are typically between about 0.05 and 10 microns in size. (Note that in traditional aerosol science, the term “aerosol” refers to both the particles and the medium in which they reside, whereas for remote sensing, the term commonly refers to the particles only. In this article, we adopt the remote-sensing definition.) They originate from a great diversity of sources, such as wildfires, volcanoes, soils and desert sands, breaking waves, natural biological activity, agricultural burning, cement production, and fossil fuel combustion. They typically remain in the atmosphere from several days to a week or more, and some travel great distances before returning to Earth’s surface via gravitational settling or washout by precipitation. Many aerosol sources exhibit strong seasonal variability, and most experience inter-annual fluctuations. As such, the frequent, global coverage that space-based aerosol remote-sensing instruments can provide is making increasingly important contributions to regional and larger-scale aerosol studies.

Aerosols affect Earth’s energy balance through direct radiative forcing – scattering sunlight back to space, which increases the top-of-atmosphere albedo over most surfaces, producing net surface cooling. Darker particles absorb some incoming light, warming the ambient atmosphere, changing cloud properties locally, and possibly altering regional atmospheric circulation patterns. Aerosols also exert “indirect” effects on clouds, as they provide cloud-condensation nuclei and ice nuclei essential for cloud particle formation, and can thus mediate cloud microphysical properties and regional water cycles. In addition, the near-surface aerosol concentration is a factor affecting local air quality. Many of these topics are explored elsewhere in this Encyclopedia (Aerosols: Climatology of Tropospheric Aerosols; Physics and Chemistry of Aerosols; Aerosols: Role in Radiative Transfer; Aerosols: Role in Cloud Physics; Satellite Remote Sensing: Cloud Properties; Precipitation). Suborbital observations, which can provide microphysical and chemical detail unobtainable from space, are covered in “Aerosols: Observations and Measurements.” **{Are there Encyclopedia entries covering *Air Quality* or *Aerosol Transport Modeling*?}**

The current article focuses on what has been and can be learned about aerosols from space-based remote sensing. Compared to the much older field of *in situ* aerosol sampling, satellite remote sensing is a blunt object, offering at present snapshots of the horizontal and vertical distribution of aerosol amount over land and water, typically at several-kilometer horizontal spatial resolution, and loose classification of aerosol type under favorable retrieval conditions. Its essential contribution is the scope of coverage, which, even in the early days of satellite imagery in 1960s, helped establish the trans-continental mineral dust pathway from the North African desert to the Caribbean (Figure 1), and has since provided regional and global context for a broad range of leading climate and health-

related aerosol questions. More recently, advanced passive imagers and active lidar systems have been flown successfully in space; we tell their story here.

Aerosol Remote Sensing Over Ocean

Two of the main challenges for satellite aerosol remote sensing are (1) separating the surface from the atmospheric contributions to the top-of-atmosphere observations, and (2) identifying the light-scattering properties of the particles, which are related to aerosol type. The first of these is dramatically reduced where satellite aerosol retrievals are performed over dark, uniform water surfaces. So early efforts to retrieve aerosol column amount from space were performed over ocean.

AVHRR – From a single red-band spectral channel centered at $0.63\ \mu\text{m}$, where the ocean surface tends to be dark, together with an assumed optical model for the particles involved, estimates of total-column aerosol amount were derived from Advanced, Very High-Resolution Radiometer (AVHRR) reflectance measurements. These revealed the seasonal patterns of major dust, smoke and pollution aerosol plumes on a global scale (Figure 2), providing both inspiration for improved aerosol measurement and modeling, and some actual constraints on chemical transport models that aimed at simulating, and to some extent predicting, the environmental impacts of airborne particles. AVHRR instruments began collecting continuous data from space in 1981, and offer a substantial time series of global aerosol distributions. Some more recent algorithms incorporate a second AVHRR spectral channel, making it possible to derive limited particle size constraints. But poor radiometric calibration accuracy and the small number of relatively broad spectral bands on these wide-swath, single-view instruments limited the quantitative application of the data to aerosol research. Similar products related to aerosol amount have been derived with higher temporal resolution from NOAA's Geostationary Environmental Satellites (GOES) and European Space Agency's Spinning Enhanced Visible and Infrared Imager (SEVIRI) geostationary instrument, and also from NASA's polar-orbiting Sea-viewing Wide Field-of-view Sensor (SeaWiFS), a space-based multi-spectral imager having much narrower and better-calibrated spectral bands than the AVHRR.

MODIS/VIIRS – Whereas the intensity of sunlight reflected by aerosols is closely related to column amount, the spectral dependence of the aerosol-reflected component contains some information about particle size. The MODerate resolution Imaging Spectroradiometers (MODIS), part of the NASA Earth Observing System (EOS), represent a second-generation of multi-spectral imagers, having 36 spectral channels spanning 0.4 to $14.4\ \mu\text{m}$, high radiometric calibration accuracy and stability, and sub-kilometer pixel resolution. These features make it possible to produce a significantly higher quality constraint on the optically equivalent aerosol column amount, generally reported as the extinction aerosol optical depth (AOD), a measure of the amount of light removed from an incident beam at a given wavelength, due to both scattering in all directions, and absorption by particles. The first MODIS instrument was launched with the EOS Terra satellite and began acquiring data in early 2000; a second MODIS began its mission on EOS Aqua in April 2002. Over ocean, MODIS top-of-atmosphere, scattered-light measurements from six visible and near-infrared spectral channels are interpreted in terms of AOD and fine-mode AOD fraction (FMF), along with estimates of the fine- and coarse-mode effective sizes, providing global coverage approximately every two days (Figure 3). A standard dark

ocean surface model is assumed, including sun-glint exclusion and wind-dependent whitecap reflectance, and particle properties are selected from a pre-determined list of likely aerosol types. The FMF is helpful in identifying aerosol type, as mechanically produced desert dust and maritime aerosols formed by breaking waves tend to be dominated by “coarse-mode” particles larger than a micron in diameter, whereas the populations of smoke, pollution, and other combustion and biogenic aerosols fall largely into the sub-micron “fine mode.”

Over-ocean AOD Trends – One important application of the regional-to-global-scale AOD time-series derived from satellite observations has been the identification of trends. Aerosol amount varies on many spatial and temporal scales, so determining systematic tendencies requires relatively long, high-precision data records, having sufficient spatial coverage and temporal frequency to account for measurement anomalies and isolated events such as volcanic ash and wildfire smoke plumes. Such analysis was first performed with 25 years of AVHRR data, and subsequently, with the first decade of carefully filtered MODIS AOD retrievals (Figure 4). The globally averaged over-ocean trend derived between 2000 and 2009 was negligible, but some significant regional AOD increases and smaller decreases were found, in most cases traced to changes in human activity. To continue this time-series, a broad-swath, multi-spectral Visible Infrared Imaging Radiometer Suite (VIIRS) imager, having capabilities in some respects similar to MODIS, was launched on the National Polar-orbiting Operational Environmental Satellite System Preparatory Project (NPP) satellite in 2011, the first in a series planned for future NOAA operational polar-orbiting satellites.

Retrieving AOD over land with comparable accuracy from space-based observations is more difficult, but significant progress has been made in this area as well.

Aerosol Remote Sensing Over Land

The land surface of Earth is generally brighter and more variable than that of the ocean. To retrieve aerosol amount and type over land from satellite observations, the typically smaller aerosol-reflected component of upwelling radiation must be distinguished from the surface-reflected component. Since the early days of satellite aerosol observation, a range of approaches has been conceived, developed, and applied to address this challenge.

TOMS/OMI – Atmospheric gas molecules scatter ultraviolet (uv) light very efficiently, partly obscuring the surface as viewed from space, and in addition, Earth’s surface tends to be darker in the uv than in the visible. So the differential absorption in two uv spectral channels from the Total Ozone Mapping Spectrometers (TOMS) instruments, which began taking data in 1979, and subsequently from the Ozone Mapping Instrument (OMI), have been interpreted as an Aerosol Index, a qualitative measure of aerosol amount, over land and water. With some assumptions and constraints on aerosol vertical distribution and on the aerosol uv absorption properties (usually represented by the single-scattering albedo (SSA, which is the ratio of fraction of light scattered to that scattered and absorbed by the particles at a given wavelength), these data also yield the AOD (Figure 5). As the retrieval is based on aerosol absorption of the upwelling uv radiation, it tends to be less sensitive to near-surface aerosol. A similar approach was used for the European GOME satellites.

MODIS Dark Target, Deep Blue, and MAIAC – Several approaches have been used to obtain AOD over land from the MODIS instruments. The “dark target” method over land relies on the 2.1 micron MODIS channel, in which atmospheric gas and aerosol opacity is generally low, to provide a constraint on the surface reflectance. The surface reflectance is then transferred to visible wavelengths where the AOD is determined, using an empirical relationship; a similar approach is used for ESA’s medium resolution imaging spectrometer (MERIS), and is planned for the next generation of US geostationary satellite multi-spectral imagers. Over land, the aerosol type used in the algorithm is assumed, based on a climatology derived from the global AErosol RObotic NETwork (AERONET) network of surface sun and sky-scanning photometers (Figure 6). AERONET also provides high-quality AOD measurements used to validate many satellite AOD products. As MODIS also has a relatively short wavelength “deep blue” channel at 0.41 microns, a variant of the uv absorption technique provides AOD from that instrument over brighter surfaces, such as desert. The combination of MODIS dark water, dark target land, and deep blue AOD products is illustrated in Figure 3a. A third approach for extracting AOD over land from MODIS relies on detecting temporal variations in the observed radiance. The changing AOD, Ångström exponent (i.e., the spectral dependence of the AOD; specifically, minus the spectral slope of AOD in log-log coordinated), and surface angular reflection properties are extracted from 16-day time-series of MODIS imagery that capture different angular views of a region, a technique called Multi-Angle Implementation of Atmospheric Correction (MAIAC).

AATSR, MISR – As Earth is viewed at steeper angles, the atmospheric contribution to the top-of-atmosphere reflectance systematically increases, and the surface is increasingly obscured. Multi-angle observations make it possible to separate surface from atmosphere based on the varying air-mass-factors through which the observations are made. The European Space Agency’s (ESA) Along-Track Scanning Radiometer-2 (ATSR-2) imagers made use of this approach with a two-angle configuration beginning in 1995, and in 2000, the NASA Earth Observing System’s Multi-angle Imaging SpectroRadiometer (MISR), with nine cameras pointed at angles ranging from 70° aft, through nadir, to 70° forward along the orbit track, began operations. AOD over land and ocean is produced from both ATSR-2 and MISR instrument data sets; ATSR also reports Ångström exponent, and MISR provides a classification of aerosol “type” under favorable retrieval conditions, based on loose aerosol size, shape, and single-scattering albedo constraints that can be derived from the multi-angle, multi-spectral data (Figure 7).

POLDER – Polarization is an additional property of light from which information about a scene can be extracted. The inclusion of polarization sensitivity with multi-spectral, multi-angle capabilities allows the French Space Agency’s (CNES), POLARization and Directionality of the Earth’s Reflectances (POLDER) series of imagers to retrieve fine-mode and total AOD over land and water. The analysis takes advantage of the relative spectral independence of polarized reflectance for most land surfaces, and the greater polarization of light scattered by smaller and more spherical particles, such as smoke or pollution, compared to larger, non-spherical desert dust. The POLDER instruments began acquiring data in 1997, and combine spectral, angular, and polarization information to monitor aerosol (Figure 8).

More About Particle Properties – In general, having constraints on particle properties improves the accuracy of AOD results for both the uv absorption and the various scattering

retrieval techniques. Knowing aerosol type is also critical for source attribution, the assessment of aerosol radiative forcing, the determination of material fluxes, and other applications that depend upon knowing the chemical or physical nature of the particles. So in addition to the multi-spectral assessment of particle size, and the multi-angle multi-spectral determination of particle type with and without polarization, several other techniques for constraining properties from space have been demonstrated, at least on a case-by-case basis.

The *critical reflection* technique relies on the idea that if particles reflect more light at a given view angle and wavelength than the surface below, the top-of-atmosphere (TOA) reflectance will increase with AOD, whereas if the particles reflect less light than the surface below, the TOA reflectance will decrease as AOD increases. So if a layer of uniform aerosol amount and type overlies a surface of varied albedo, some parts of the scene will be brightened more than others by the aerosols. From images of the scene on several days when the aerosol type is similar but the AOD is different, the SSA of the particles can be deduced. As aerosol properties for a given source in a given season tend to be repeatable, even if the amount of aerosol varies considerably, this is a credible approach for deriving aerosol type information over variable land surfaces in some locations.

Other methods combine the capabilities of several instruments to help constrain underdetermined remote-sensing retrievals. For example, the TOMS and OMI uv AOD retrievals are sensitive to particle SSA and aerosol vertical distribution, and pixels several tens of kilometers in size from these instruments can be affected by undetected sub-pixel clouds. Combining TOMS or OMI observations with near-coincident MODIS AOD and relatively high-spatial-resolution cloud clearing can produce more accurate constraints on SSA. When aerosol vertical distribution from an active sensor such as the NASA Earth Observing System's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Figure 9) are included, even tighter constraints can be derived on aerosol properties and scene conditions. Similarly, data from the two-angle-viewing AATSR, providing AOD and cloud identification at relatively high spatial resolution, have been combined with high-spectral-resolution observations from the SCanning Imaging Absorption spectromETER for Atmospheric CHartographyY (SCIAMACHY) spectrometer, both aboard ESA's ENVISAT, to distinguish mineral dust, sea salt, soot and water soluble aerosol types.

With recent technological advances and the demonstrated value of multi-angle, multi-spectral, polarizing imagery covering the uv through the visible into the near infrared, future satellite aerosol instruments will likely combine all these capabilities into a single passive, broad-swath, remote-sensing imager.

Constraints on Climate Models

Synthesizing the collection of observations into a global picture while taking account of the relative strengths, limitations, and gaps in the various data records is a challenge in itself. But it is an essential step in applying the measurements to short-term forecast models, and to longer-term climate models, which are the primary tools for diagnosing many atmospheric processes, and for making predictions. One approach has been to assimilate the observations into models, "nudging" the model AOD based on available measurements.

The frequent (one-to-two-day) global coverage of the MODIS AOD data has been successfully used to improve several-day AOD model forecasts, once the satellite data set was filtered to remove outliers and retrievals that might have been affected by unscreened cloud, leaving about 50% of the original points.

For longer-term climate modeling, more uniform global products are generally required. Monthly, global maps of AOD were created from the combination primarily of MODIS, MISR, and surface-sun-photometer AERONET data. These are being used to constrain leading numerical climate models. In this case, the frequent coverage of MODIS over water, the approximately once-weekly but generally more accurate over-land AOD from MISR, and the most accurate AERONET data, but with only spot sampling, were the main components aggregated into a unified AOD product (Figure 10).

Knowing aerosol vertical distribution is especially important for climate modeling, as aerosol reflection and absorption of sunlight at different levels in the atmosphere not only alter the surface energy budget, but can affect the atmospheric stability structure, regional-scale atmospheric circulation, and aerosol impacts on clouds. The vertical distribution is also critical for assessing aerosol transports, as aerosols residing above the atmospheric boundary layer tend to stay aloft longer, travel farther, and have greater environmental impact. The CALIPSO lidar generates a curtain of backscatter profiles at two wavelengths and having polarization sensitivity, with up to about 330 m horizontal resolution and 30 m vertical resolution. Some vertically resolved aerosol type classification is also possible with these data. Coverage is limited to the width of the lidar beam, which means most aerosol sources are missed, but the great sensitivity of the observations to very thin aerosol layers far downwind of sources provides accurate snapshots that can be aggregated into general climatological constraints (Figure 9b-e).

Aerosols are usually introduced into models by providing an inventory of *injection heights*, *source strengths*, and locations for different aerosol types. Aerosol injection heights, derived from the parallax in multi-angle imaging views of aerosol plumes, can provide such information (Figure 11). Unlike lidar, stereo imaging requires aerosol plumes to exhibit discrete features that can be tracked in multiple angular views, so the technique applies mainly within a few hundred kilometers of major aerosol sources such as wildfires, volcanoes, and places where desert dust storms form. So the lidar and stereo-imaging techniques are complementary; as aerosols tend to travel in discrete layers, having upwind injection height from multi-angle imaging and downwind layer heights from space-based lidar combine to provide powerful constraints on model simulations of aerosol vertical distribution.

Efforts to determine aerosol source strength from satellite observations all involve tight coupling between available measurements and the aerosol transport models themselves. The inverse modeling approach takes the observed AOD distribution over a wide area and in effect, runs the model backwards to derive the sources. An alternative method involves running the model forward for a range of assumed source strengths and whatever constraints on injection height are available, and determines which assumed values best match the observed snapshot of AOD spatial distribution at the appropriate time step. Both methods have been demonstrated for individual cases (Figure 12), motivating continuing work to generalize these results.

One of the main applications for which frequent, global satellite aerosol observations are required is direct aerosol radiative forcing (DARF), the net change in energy flux (e.g., in W/m^2) at the surface produced directly by aerosol scattering and absorption. Uncertainty in the amount of surface cooling aerosols produce is a limiting factor in determining the ability of climate models to predict changes in global mean surface temperature. Given the accuracy with which the radiative warming of long-lived greenhouse gases can be calculated, the required accuracy on aerosol properties to bring this factor into line is quite stringent. It is estimated that instantaneous, mid-visible AOD measurements need to be accurate to about 0.02 over much of the globe. Current capabilities are of order 0.05 or 20% of AOD, whichever is larger, over land, and somewhat better over dark water. Some improvement is expected as the algorithms used for current operational instruments are refined, but a substantial advance will likely require a next-generation space-based instrument, combined with better constraints on particle microphysical properties that will probably require a systematic program of aircraft and surface-based direct sampling along with continued surface-based remote-sensing (such as AERONET).

Applications to Cloud Formation and Air Quality

One of the most challenging questions to which satellite observations have been applied is assessing aerosol impacts on clouds, often call aerosol “indirect” effects, as distinct from the direct radiative forcing aerosols produce. Aerosols are essential for cloud droplet and ice particle formation; they serve as collection sites for water molecules, referred to as cloud condensation nuclei (CCN) and ice nuclei (IN), respectively.

Aircraft instruments are generally best suited to study indirect effects in detail, as they can sample the 10s-to-100s-of-meters spatial and minutes-to-hours temporal scales that capture the cloud development process. Nevertheless, satellite instruments have a contribution to make, taking advantage of the frequent, global coverage they offer, for exploring larger-scale patterns. With imaging from passive remote sensing, cloud albedo, cloud droplet radius, and cloud optical depth can be mapped, along with cloud top temperature and pressure, aerosol amount, and aerosol type. However, typical CCN populations are skewed toward particle sizes that remote sensing techniques cannot distinguish from atmospheric gas molecules. So efforts have been made to identify proxies derived from those parts of the aerosol size spectrum that can be retrieved from space. In addition, the aerosol retrieval process itself is hampered by the presence of clouds – particles residing beneath clouds, in the critical cloud droplet formation regions, usually cannot be detected from orbit, and aerosol retrievals in the vicinity of clouds are often complicated by the influence of large relative-humidity gradients and cloud-scattered light. As a result, most space-based studies of indirect effects amount to mining the satellite data for correlations that test theoretical expectations about how aerosol impact clouds.

Figure 13 (a-c) presents examples of correlations between aerosol amount and cloud droplet size, in two situations where there are both perturbed and unperturbed observations of the same environments. All other things being equal, increasing aerosol amount is expected to result in smaller cloud droplets (what is commonly called the “first indirect effect”), and if the amount of condensed water in the cloud remains constant, higher cloud albedo. Globally, this qualitative relationship is observed in some regions more than others (Figure 13d); the most reliable demonstrations involve liquid water

clouds relatively near the surface. Other consequences of aerosol impacts on clouds include longer cloud lifetimes and reduced precipitation, due to smaller cloud droplets that are less likely to grow to raindrop size, though these have been more difficult to demonstrate, let alone quantify, with satellite remote sensing.

However, space-based measurements have observed cloud “invigoration” (Figure 13e). Here higher concentrations of CCN reduce the size of cloud droplets, inhibiting droplet coalescence until the droplets pass the freezing level. The resulting extra release of energy invigorates the cloud, increasing the cloud fraction and enhancing precipitation. Other recent work has demonstrated a relationship between aerosol concentration and open vs. closed convective cell formation, and has shown a correlation between AOD and lightning occurrence as observed from space.

Air quality is monitored primarily with surface-based sampling instruments that directly observe the near-surface particle concentration and can obtain detailed information about particle size distribution and chemical composition. But as it is feasible to cover only a minuscule fraction of the planet with surface samplers, satellite observations can again play a significant role, simply by providing frequent maps of AOD during acute air pollution events. They are also beginning to contribute to longer-term exposure studies, especially when combined with chemical transport model results that provide particle vertical distribution and chemical speciation that is otherwise lacking observationally (Figure 14).

Conclusions

Because aerosol amount and type vary on such a wide range of spatial and temporal scales, and exhibit such a diversity of environmental impacts, satellite remote sensing makes an essential contribution to the study of airborne particles. Since the very first orbiting imagers began observing Earth, the scope of satellite data products has provided inspiration, qualitative indications, and increasingly, quantitative constraints on the regional and global influences aerosols exert. Major advances in this field have taken place in the last decade, since the previous edition of the *Encyclopedia of Atmospheric Science* was published, from monthly, global AOD climatologies and time series, to near-source and downwind aerosol vertical distribution measurements, regional aerosol type discrimination, aerosol source strengths, and correlative analyses showing the indirect effects of aerosols on clouds. Much of this advance has come from the current generation of satellite instruments, increasingly sophisticated aerosol field measurement campaigns, ground-based instrument networks, and from combining data from multiple sources with models. Further advances can be expected as retrieval algorithms continue to be refined, as data and models are analyzed and combined in new and innovative ways, and eventually, as next-generation space-based aerosol remote-sensing instruments are deployed.

See also

Aerosols: Climatology of Tropospheric Aerosols; Observations and Measurements; Physics and Chemistry of Aerosols; Role in Cloud Physics; Role in Radiative Transfer. **Dust.**
Satellite Remote Sensing: Cloud Properties; Precipitation.

Further Reading

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Figure Captions

Figure 1. (a) Trajectory of a Saharan dust plume, tracked over eight days from the source region in North Africa across the Atlantic Ocean to the Caribbean, based on images from a wide-swath vidicon camera aboard the polar-orbiting ESSA 5 satellite. (b) ESSA 5 satellite image of the plume (indicated by white arrow) over Mauritania, Western Sahara, and the eastern Atlantic on 7 June 1967. Dust particles more than 20 μm in diameter from this storm were recovered subsequently in Barbados. [From: *Prospero et al., Earth & Planet. Sci. Lett.* 9, 1970, pp. 287-293.]

Figure 2. Global, over-ocean estimates of total-column aerosol amount for the northern (a) winter and (b) summer seasons, derived from two years (July 1989-June 1991) of mid-visible reflectance measurements from the Advanced, Very High-Resolution Radiometer (AVHRR) instruments aboard NOAA polar-orbiting satellites. The winter peak in grassland burning produces a smoke plume over the Atlantic west of the sub-Sahara region, whereas in summer, dust from northern Africa and smoke from central Africa produce plumes over the adjacent water, and dust from the Middle East blankets the Arabian Sea. Pollution sources off the east coast of China vary little between these two seasons, whereas pollution off the east coast of the United States is more prominent in summer. [From: *Husar, Prospero, and Stowe, J. Geophys. Res.* 102, 1997, pp. 16889-16909]

Figure 3. Figure 3. MODIS global, monthly average aerosol products for July 2010. (a) AOD from the combination of “dark target” and “deep blue” algorithms, and (b) fine-mode fraction (FMF) over ocean, with AOD, related to the confidence with which FMF can be

determined, encoded as the saturation of the color applied, all derived with the dark target algorithm. [From: *MODIS Team, NASA Goddard Space Flight Center*]

Figure 4. Global/Regional, over-water, (a) mid-visible AOD trends and (b) associated confidence levels, derived from ten years (2000-2009) of MODIS operational aerosol products. The MODIS time-series was first filtered to remove outliers and reduce possible cloud contamination, and calibrated using less frequent but more accurate MISR and AERONET observations. Confidence levels were assessed as the derived trend (ω), normalized by the estimated time series standard deviation (σ_ω), on $1^\circ \times 1^\circ$ grid cells. Increasing AOD trends are found over the Bay of Bengal, east coast of Asia, and Arabian Sea, whereas weaker, AOD decreases were derived off Central America, the east coast of North America, and the west coast of Africa. [From: *Zhang and Reid, Atmos. Chem. Phys, 10, 2010, doi:10.5194/acp-10-1-2010*]

Figure 5. TOMS Aerosol Data Products. (a) Aerosol Index (AI) map over south and southeast Asia and surrounding water, for 13 April 2001. Dust over central Asia, smoke and pollution aerosol over southeast Asia, and dust combined with pollution over east-central Asia stand out. [Hsu, et al., *Geophys. Res. Lett.*, 23, 1996, pp. 745-748.] (b) Zonal-average AOD time-series at 380 nm, covering 1979-1992 and 1996-2000. Note the prominent volcanic plumes from El Chichon in 1982 and Mt. Pinatubo in 1991, each lasting many months. [From: *Torres et al., J. Atmosph. Sci. 59, 2002, pp. 398-413*]

Figure 6. Averaged particle spectral single-scattering albedos (SSA) and size distributions for several sites dominated by Pollution, Smoke, Dust, and Oceanic aerosols, as derived from AERONET surface-based sun photometer measurements. AOD at 440 nm for the cases shown are indicated as " τ_{440} ," the real part of the particle refractive index is given as "n," and the spectral dependence of the AOD (Ångström exponent), evaluated at 440 and 870 nm, is designated " α " in this figure. Note how the size distributions vary with aerosol type, and how SSA varies considerably even within the Urban/Industrial and Biomass Burning categories. [From: *Dubovik et al., J. Atmosph. Sci. 59, 2002, pp. 590-608*]

Figure 7. . MISR (a) true-color, nadir viewing image of a Saharan Desert dust plume over the Atlantic Ocean north and east of the Cape Verde Islands (which are visible in the center of the image), and retrieved (b) AOD, (c) Ångström exponent, and (d) fraction AOD non-spherical. North is roughly toward the top of the images, and the swath is about 380 km wide. The plume has higher AOD, and the dust particles are larger (i.e., smaller Ångström exponent) and more non-spherical compared to background values. [From: *MISR Team, NASA Goddard Space Flight Center and Jet Propulsion Lab/Caltech*]

Figure 8. Three-month (Sept.-Nov.), global fine-mode AOD at 550nm over land and water, derived from POLDER observations: (a) averaged over five years (2005-2009), and (b-f) AOD anomaly for each individual year. Blue in the anomaly panels indicates the AOD for that year was lower than the longer-term mean, whereas red indicates higher values. Note the high inter-annual variability in the biomass burning regions of Brazil, southern Africa, Indonesia, and the northern boreal latitudes. [Adapted from: *Tanré et al., Atmos. Meas. Tech. 4, 2011, pp. 1383-1395, doi:10.5194/amt-4-1383-1395-2011*]

Figure 9. CALIPSO vertical profiles. (a) Backscatter curtain plot, showing cloud and aerosol layers over the region highlighted in dark blue in the adjacent context map. Spectral and depolarization lidar signals identify transported dust (yellow arrow)

overlying a surface layer of polluted continental aerosol (red arrow). Clean maritime and maritime mixed with dust and pollution particles (cyan arrow) are found farther south along the orbit track. [From: *CALIPSO Team, NASA Langley Research Center*] (b-e) Seasonally aggregated dust (orange) and non-dust, mainly smoke and pollution (blue) vertical extinction profiles over Eastern China in 2007. Note how the vertical extent is a minimum in the autumn (SON) and winter months (DJF), and that dust amount peaks in the winter and spring (MAM) seasons. The total column AOD (τ_c) and effective aerosol scale height (H_c) are indicated in each panel. [From: *Yu et al., J. Geophys. Res. 115, D00H30, 2010, doi:10.1029/2009JD013364.*]

Figure 10. Maps of multi-year, annual-average, mid-visible aerosol optical depth (AOD) from multiple remote-sensing data sets: Mi=MISR, Mo=MODIS land+water, Mn=MODIS over-ocean, Po=POLDER, To=TOMS, An, Ag=AVHRR (1- and 2-channel retrieval algorithms, respectively); Ae=AERONET ground-based sun photometer network. A “synthesis” of these AOD products (S^*), primarily from MISR, MODIS, and AERONET, used extensively for model validation, is highlighted in red. The global-average AOD for each data set is given below its label. [From: *Kinne et al., Atmos. Chem. Phys. 6, 2006, pp.1815–1834*]

Figure 11. Satellite views of the Station Fire that burned in the Los Angeles California area in late August and early September 2009. (a) True-color image from the MISR nadir-viewing camera on 30 August 2009, showing smoke plumes from multiple active fires, and an arc-shaped cloud upwind of the fire front, possibly formed by incoming air forced to rise over the buoyant air mass heated by the fires. Pyrocumulus clouds, formed over several highly convective spots in the burning region, appear as small white dots above the smoke plume. (b) MISR stereo-derived plume heights, reported as values above sea level, for individual pixels 1.1 km in size. [From: *MISR Team, Jet Propulsion Lab/Caltech and NASA Goddard Space Flight Center*]

Figure 12. Characterizing aerosol source strength. (a) Average of daily global MODIS fine-mode AOD maps covering August 18-30 2000. (b) Retrieved emission source location and strength from inverse run of the GOCART chemical transport model at $2^\circ \times 2.5^\circ$ resolution, constrained by (a). [From: *Dubovik et al., Atmos. Chem. Phys. 8, 2008, pp.209–250*] (Second row; c-j) Successive panels showing: MODIS visible image of a Siberian wildfire smoke plume on 20 July 2006; MODIS retrieved AOD snapshot from the standard product at 10 km spatial resolution; MODIS AOD averaged to the GOCART model $1^\circ \times 1.5^\circ$ grid; AOD snapshots taken at MODIS overpass time from five GOCART model runs, each initialized with different, commonly used parameterizations for smoke source strength. For wildfires in different biomes around the globe, different initialization choices performed systematically better compared to the corresponding MODIS observations. [From: *Petrenko et al., J. Geophys. Res. 117, D18212, 2012, doi:10.1029/2012JD017870*]

Figure 13. Indirect effects of aerosols on clouds. (a) Ship tracks off the coast of California, as viewed by AVHRR. (b) Retrieved cloud droplet radius (r_c) and cloud optical depth (τ_c) differences between observations within the polluted ship tracks and those in the surroundings, showing a decrease in droplet size in the polluted tracks. [From: *Coakley and Walsh, J. Atmosph. Sci. 59, 2002, pp. 668-680*]. (c) Red color indicates regions where large droplets were retrieved in this false-color AVHRR image encoding two infrared and one visible spectral channels, whereas yellow trails emanate from point sources of smoke that produce smaller droplets in this fairly uniform cloud deck over south Australia. [From: *Rosenfeld, Science 287, 2000 pp. 1793-1796*] (d) Illustration of the correlation between

retrieved particle number concentration (N_a) and cloud droplet concentration (N_c) globally, based on AVHRR measurements, aggregated over four months during 1990; Yellow indicates high N_c in the presence of large N_a , whereas regions of high N_c despite small N_a appear red. [From: *Nakajima et al., Geophys. Res. Lett.* 28, 2001, pp. 1171-1174] (e) Evidence from MODIS retrievals for invigoration of Atlantic convective clouds; panels show (clockwise from upper left) cloud top pressure (p_c), cloud fraction (C_f), cloud droplet effective radius (r_c), and cloud optical depth (τ_c) as a function of elevation, with AOD encoded in colors, increasing from blue to red to purple and green. [From: *Koren et al., Geophys. Res. Lett.* 32, 2005, doi:10.1029/2005GL023187]

Figure 14. Six-year (2001-2006), global average, near-surface concentration of particles smaller than 2.5 microns diameter (PM_{2.5}) over land, derived from MISR+MODIS total-column AOD, combined with vertical distribution from the GEOS-Chem chemical transport model. The vertical distributions were validated using CALIPSO profiles, and derived PM_{2.5} can be compared with surface-station values, which are shown using the same color scale, superposed where available within black circles in this figure. [From: *Van Donkelaar, et al., Environ. Health Perspect.* 118, 2010, pp.847-855]