11 Conclusion: Results and suggestions for future research

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11.1 Summary

Aerosols are a complex and important component of the atmosphere. These particles consist of various chemical compositions (homogeneous or inhomogeneous), shapes and sizes, and they affect human health, the environment, visibility, and atmospheric chemistry. A major concern is their influence on climate, directly by modifying the Earth's radiation budget, and indirectly by modifying cloudiness, cloud properties, precipitation and atmospheric circulations. The aerosol influence does not depend only on their total amount, as it is the case for the gaseous components of the atmosphere, but on their chemical composition, shapes, and sizes.

Because of aerosol importance, and spatial and temporal variability, aerosols require constant characterization and monitoring, and a global perspective. In situ measurements are critical to provide details of understanding, but these observations are relatively sparse and infrequent. A global perspective can be achieved only by remote sensing, performed either from the Earth's surface or by satellite-borne instruments. Ground-based and satellite remote sensing provide complementary information, with the ground-based instruments providing validation for satellite retrievals and sometimes a broader suite of retrieved parameters than can be achieved from space, while satellite remote sensing provides the true global perspective. Remote sensing measurements are based on the complex impact of aerosol on radiation. This complexity makes retrieval of aerosol from remote sensing data a difficult task.

The simplest remote sensing instrument is the ground-based sunphotometer, which provides the aerosol total optical depth, i.e. an information on the total amount of aerosol weighted by their extinction coefficient, at one or several wavelengths. Even in this case,

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the required quality of measurements is dependent on the design, fabrication, calibration and operation of the instrument (Chapter 4, Section 4.2). The optical depth is obtained directly, but when one tries to extract further information, as the aerosol size distribution, from the spectral distribution of optical depth, one is faced with a difficult inversion problem (Chapter 5, Section 5.2). Figure 5.1.b shows the overlap of the extinction kernels for four wavelengths between 0.44 and 1.02 μm, meaning that they all carry similar information; therefore increasing the number of wavelengths in this interval cannot improve the retrieval. Extending the spectral interval to around 2.0 μm brings some more information, but does not permit retrievals of parameters such as single scattering albedo or refractive index. However, more information can be sought by adding independent observations, such as the sky radiance distribution, and the sky polarization to the direct sun observation. The analysis of this large set of data requires complicated retrieval algorithms, but enables retrieval of many more aerosol characteristics (Chapter 5, Section 5.8). Table 11.1 lists some prominent sources of publicly-available aerosol information derived from suborbital (ground-based or airborne) instruments.

Instrument	**Network or platform**	**Period**	**Wavelengths or bands (μm)***	**Parameter**	**Reference**
AATS	Various airborne platforms	1985-present	14(0.354–2.139)	τ,α	Matsumoto et al. (1987) Livingston et al. (2005)
Cimel	AERONET	1993-present	7(0.34–1.02)	τ,α, ϖ %spherical dV/dlnr, m_r+im_i, p(Θ)	Holben et al. (1998) Dubovik and King (2000)
Prede POM	SKYNET	1998-present	7(0.315–1.02)	τ,α, ϖ %spherical dV/dlnr, m_r+im_i, p(Θ)	http://atmos.cr.chiba-u.ac.jp/
Microtops II	Marine Aerosol Network	2004-present	5(0.34–1.02)	τ,α	Smirnov et al. (2009)

* Primary bands used in aerosol retrieval. If the sensor contains additional bands aerosol retrievals often also make use of a wider spectral range than what is listed here for cloud masking, etc.

Table 11.1 Suborbital (ground-based or airborne) passive instruments, platforms and networks, providing total column characterization of aerosol

The occultation instruments are dedicated to characterizing the high atmospheric layers. They measure directly a slant aerosol optical thickness, and are based on the same principles as ground based sunphotometry (Chapter 4, Section 4.3). The aerosol data record produced by the occultation instruments provides nearly a 30 year characterization of stratospheric aerosol, covering multiple important volcanic eruptions (Chapter 7, Sections 7.2 and 7.3). Table 11.2 lists the important occultation instruments.

Earth-viewing nadir observations began with instruments using one or two wavelengths, either in the visible and near-IR or in the near-UV. These heritage instruments were used to retrieve the total aerosol optical depth and, in the case of the near-UV instruments, the Absorbing Aerosol Index. The retrieval algorithms were generally based on look-up tables (LUT), required several assumptions in the retrievals and were limited to specific land surface types (Chapter 7). Nowadays, several sophisticated spaceborne instruments observe aerosols; most of them use the backscattered solar radiation between near ultraviolet to near infrared and make use of multiangle views of the same scene and/or polarization (Chapters 7 and 8). Table 11.3 provides a long list of earth-viewing passive sensors using

Sensor	**Platform**	**Period**	**Wavelengths or bands (μm)***	**Parameter**	**Reference**
SAM	Apollo-Soyuz	1975-1975	0.83	σ_e	McCormick et al. (1979)
SAM-2	Nimbus-7	1978-1993	1.00	σ_e	McCormick et al. (1979)
SAGE	AEM-B	1979- 1981	2(0.45,1.00)	σ_e	Chu and McCormick (1979)
SAGE-2	ERBS	1984-2005	4(0.386–1.02)	σ_e, r_{eff}, SAD	Chu et al. (1989)
POAM-2	SPOT-3	1993-1996	5(0.353–1.060)	σ_e	Lumpe et al. (1997)
HALOE	UARS	1991-2005	4(2.45,3.40, 3.46, 5.26)	σ_e, r_{eff}	Hervig et al. (1998)
POAM-3	SPOT-4	1998-2005	5(0.354–1.020)	σ_e	Lumpe et al. (2002)
SAGE-3	METEOR-3M	2001-2005	9(0.385–1.545)	σ_e	Thomason et al. (2007)

* Primary bands used in aerosol retrieval. If the sensor contains additional bands aerosol retrievals often also make use of a wider spectral range than what is listed here for cloud masking, etc.

Table 11.2 Occultation sensors and their platforms used in aerosol measurements from space, providing profiles through the stratosphere and upper troposphere

Sensor	**Platform**	**Period**	**Wavelengths or bands (μm)***	**Parameter**	**Reference**
MSS	Landsat ERTS-1	1972-1978	4(0.5–1.1)	τ	Griggs (1975)
VISSR	GOES-1-12	1975-present	1(0.65)	τ	Knapp et al. (2002) Prados et al. (2007)
VISSR	GMS-1-5	1977-2005	1(0.67)	τ	Masuda et al. (2002) Wang et al. (2003)
CZCS	NIMBUS-7	1978-1986	4(0.443–-0.67)	Atmos corr	Fraser et al. (1997)
TOMS	NIMBUS-7	1978-1993	6 (0.312–0.380)	τ_{UV}, AAI	Torres et al. (2002) J. Herman et al. (1997)
AVHRR	NOAA-6-16	1979-present	2(0.65,0.85)	τ	Stowe et al. (1997) Mishchenko et al. (1999b)
TM	Landsat-5	1982-present	7(0.452–2.347)	τ	Tanré et al. (1988)
VIRS	TRMM	1997-present	2(0.63, 1.61)	τ,α	Ignatov and Stowe (2000)
ATSR-2	ERS-2	1995-2011	4(0.55–1.6)	τ	Veefkind et al. (1999)
GOME	ERS-2	1995-2003	spectrometer (0.24–0.79)	τ, AAI	Torricella et al. (1999), de Graaf et al. (2005)
TOMS	Earth Probe	1996-2005	6(0.309–0.360)	τ_{UV},ϖ, AAI	Torres et al. (2002)
POLDER-1	ADEOS	1996-1997	7(0.443–0.97)	τ,α,η, %spherical	Herman et al. (1997)
SeaWiFs	OrbView -2	1997-present	3(0.510–0.865)	τ	Gordon and Wang (1994) Sayer et al. (2011)

Table 11.3 Passive shortwave Earth-viewing sensors and their platforms used in aerosol measurements from space, providing total column measurements

MODIS	TERRA	2000-present	8 (0.41–2.13)	τ, η	Remer et al. (2005) Levy et al. (2010)
MISR	TERRA	2000-present	4 (0.45–0.87)	τ,α, SML,ϖ, %spherical, plume ht	Martonchik et al. (2009) Kahn et al. (2010)
MODIS	AQUA	2002-present	8 (0.41–2.13)	τ, η	Remer et al. (2005)
AATSR	ENVISAT	2002-present	4(0.55-1.6)	τ	Grey et al. (2006)
MERIS	ENVISAT	2002-present	4(0.412–0.865)	τ	Vidot et al. (2008)
SCIAMA-CHY	ENVISAT	2002-present	spectrometer (0.24–2.4)	AAI	De Graaf et al. (2005)
POLDER-2	ADEOS-2	2002-2003	7(0.443–0.97)	τ,α,η, %spherical	Herman et al. (1997)
GLI	ADEOS-2	2002-2003	10(0.38–0.865)	τ, α	Murakami et al. (2006)
SEVIRI	MSG-1	2002-present	3(0.635–1.640)	τ	Popp et al. (2007)
OMI	AURA	2004-present	3(0.27–0.5)	τ, ϖ, AAI	Torres et al. (2007)
POLDER-3	PARASOL	2004-present	7(0.443–1.02)	τ, α,η, %spherical	Herman et al. (1997) Tanré et al. (2011)
GOME-2	Metop-A	2006-present	spectrometer 0.24–0.79	τ, AAI	De Graaf et al. (2005)
CAI	GOSAT	2009-present	4(0.380–1.60)	τ	Sano et al. (2009)
VIIRS	NPP	2011-present	9(0.412–2.25)	τ,α	Northrup Grumman Space Technology, ATBD RevF (2010)

* Primary bands used in aerosol retrieval. If the sensor contains additional bands aerosol retrievals often also make use of a wider spectral range than what is listed here for cloud masking, etc.

observations in the shortwave spectrum that have been used for aerosol retrieval. Most of these sensors have either a long history of aerosol retrievals or were designed for aerosol retrieval, and many, but not all, make their aerosol products available to the public. A few sensors in Table 11-3 are included for historical interest.

Research on characterizing aerosol based on the observation of longwave (terrestrial) radiation shows very promising results (Chapter 9). However, to date the only operational

Sensor	**Platform**	**Period**	**Wavelengths or bands (μm)***	**Parameter**	**Reference**
CLAES	UARS	1991–1993	8(5.3–12.8)	σ_e	Roche et al. (1993) Massie et al. (1996)
ISAMS	UARS	1991–1992	6.21,12.1	σ_e	Taylor et al. (1993)
HIRDLS	Aura	2004-present	5(7.1–17.4)	σ_e	Khosravi et al. (2009)

* Primary bands used in aerosol retrieval. If the sensor contains additional bands aerosol retrievals often also make use of a wider spectral range than what is listed here for cloud masking, etc.

Table 11.4 Infrared sensors and their platforms used in aerosol measurements from space, providing characterization of aerosol in stratosphere and upper troposphere

Sensor	**Platform**	**Period**	**Wavelengths or bands (μm)***	**Parameter**	**Reference**
MVIRI	Meteosat	1982–2006	10.5–12.5	IDDI	Legrand et al. (2001)
AIRS	Aqua	2002–present	3.74–4.61, 6.20–8.22, 8.8–15.4	$\tau(10\mu m)$, altitude, r_{eff}	Pierangelo et al. (2004b; 2005a), Peyridieu et al. (2010a)
IASI	Metop	2007–present	3.62–15.5	$\tau(10\mu m)$, altitude, r_{eff}	Peyridieu (2010c)

* Primary bands used in aerosol retrieval. If the sensor contains additional bands aerosol retrievals often also make use of a wider spectral range than what is listed here for cloud masking, etc.

Table 11.5 Infrared sensors and their platforms used in aerosol measurements from space, providing total column retrievals of aerosol products retrieved from the longwave part of the spectrum are retrievals of aerosol extinction in the upper atmosphere. These are listed in Table 11.4. Some interesting aerosol retrievals through the total atmospheric column using longwave radiation, still experimental, are listed in Table 11.5.

Lidar observations using a laser as the source of radiation have the main advantage of providing information on the aerosol vertical profile (Chapter 10). While suborbital lidar has been producing important insight on aerosol vertical distribution for decades, the organization of lidar instruments into networks or the data into easily accessible archives began more recently. Table 11.6 lists a few representative suborbital lidar systems with archived data. There have been only three space-based lidars designed for aerosol characterization and these are listed in Table 11.7.

Lidar type	**Network or platform**	**Period**	**Wavelengths or bands (μm)**	**Parameter**	**Reference**
Backscatter micropulse	MPLNet	2000-present	0.523 or 0.527	σ_b	Welton et al. (2001)
Raman	EARLINET	2000-present	0.351/0.355	σ_b	Matthias et al. (2004)
HSRL	Airborne LaRC B200	2006-present	0.532, 1.064	$\sigma_{b,}$ σ_e, depol	Hair et al. (2008)

Table 11.6 Suborbital lidar instruments and networks, providing profiles through at least the lower atmosphere

Sensor	**Platform**	**Period**	**Wavelengths or bands (μm)**	**Parameter**	**Reference**
LITE	Space Shuttle Discovery	1994-1994	3(0.355,0.532, 1.064)	σ_b	McCormick et al. (1993) Gu et al, (1997)
GLAS	ICEsat	2003-2003	2(0.532, 1.064)	σ_b	Spinhirne and Palm (1996) Spinhirne et al. (2005)
CALIOP	CALIPSO	2006-present	2(0.532,1.064)	$\sigma_{b,}$ depol	Z. Liu et al. (2005) Winker et al. (2009)

Table 11.7 Satellites and lidar instruments used in aerosol measurements from space, providing profiles through the entire column

Symbols defined below are applicable for all tables, 11.1 through 11.7.

(Acronyms are defined in the list of symbols and acronyms)

τ	Aerosol optical thickness that includes a value in the midvisible but may include values across the indicated range of wavelengths
τ_{UV}	Aerosol optical thickness available only for ultraviolet wavelengths
α	Ångström exponent
ϖ	The single scattering albedo
% spherical	The percentage of the coarse mode τ due to spherical particles
η	The fraction of the total τ at 550nm due to fine particles (Section 8.3)
m_r	The real part of the refractive index
m_i	The imaginary part of the refractive index
$p(\Theta)$	Phase function
σ_e	Extinction coefficient
σ_b	Backscattering coefficient
r_{eff}	Particle effective radius
SAD	Surface area density
AAI	Absorbing aerosol index (Section 7.5)
SML	The ability to distinguish Small, Medium and Large sizes
Atmos corr	Instrument derived aerosol only as a by product and that atmospheric correction of surface reflectance was the primary product (Section 6.5)
depol	Measurements of depolarization (Section 10.6)
IDDI	Infrared Difference Dust Index (Section 9.5)
plume ht.	Plume height (Section 8.8)

11.2 Results

Remote sensing observations have provided new insight and better understanding of the global aerosol system. For example, discovery of arctic haze by ground based sunphotometers (chapter 6), observation of volcanic particles dispersion around the globe, and slow decrease after El Chichon and Pinatubo eruptions by SAGE instruments (chapter 7, section 7.3), cross-oceanic transport of desert dust and other particles (figures in Chapter 8). Furthermore, the day-to-day work of these sensors acquiring data and the application of inversions and retrieval algorithms to the data create an ever-growing climatology of aerosol properties. We see individual events (Figures 7.6, 7.7, 7.8, 8.4), the long-term average conditions (Figures 6.7, 8.5, 8.7) and the anomalies from those conditions (Figure 8.5), and the gradual trends of aerosol characteristics over time (Figures 7.4, 7.9, 8.2).

Global aerosol climatologies from various instruments are now available. Availablity does not necessarily indicate useability for a particular application such as estimating the aerosol effect on climate forcing. What confidence do we have in these results ? How accurate are the aerosol optical depth retrievals ? What of the other particle properties such as single scattering albedo and particle size ? How much confidence do we have in reported trends such as shown in Figure 7.4 ? Before blindly using remote sensing aerosol products in climate studies or other applications we need to quantify the accuracy or statistical confidence of the product or parameter. This raises the issue of validation of remote sensing products, an on-going effort addressed by all groups involved in providing data and measurement analysis. The references listed in the tables of this chapter provide a starting point to obtain information on the aerosol retrieval, data archive, uncertainties and limitations of that instrument and products. Some limitations are also discussed in Chapter 8.

11.3 Algorithms vs. Products; Validation vs. intercomparison

A distinction must be made between validating a product and validating an algorithm. Algorithms are mathematical constructs that turns an idealized set of measurements of the radiation field into information of aerosol particles theoretically embedded in that field. In a perfect world, validating an algorithm would be the same as validating the products resulting from that algorithm, but the world is not perfect. Input radiances are subject to instrumental defects : calibration drift, crosstalk from nearby channels, missing and bad detectors, and point-spread functions that smear light reflected from one pixel into nearby pixels. Furthermore, real-world algorithms must contend with identifying the scenes that are appropriate for retrieval for a certain algorithm and masking inappropriate scenes. Situations such as clouds, sun glint, snow have traditionally been masked by various retrieval algorithms, and decisions as to where to draw the threshold between appropriate and inappropriate scenes are highly subjective. Finally, data aggregation from instrument pixel size to standard product size, and then from standard product size to climate appropriate spatial and temporal means introduces a new set of subjective decisions that can create differences in global mean aerosol optical depth of 40% (Levy et al., 2009).

Algorithms can be validated as part of the process of validating products, but the distinction must be understood. A highly capable instrument measuring multispectral multi-angular and polarization with the right algorithm should return the most information of the aerosol field with the highest accuracy. However, that highly capable algorithm may not produce a better aerosol product than a single wavelength, single angle radiometer if the calibration on the polarimeter is poor, the pixels are unregistered, etc. Therefore both algorithms and products should be validated, but we note that it is much easier to validate an algorithm than a product.

In order to validate a product measured by a specific instrument, it is necessary to have another independent and reliable measure of the same parameter, given by another instrument, at the same time and in the same place. This situation almost never occurs.

Most generally space observations are «validated» using ground based observations, from networks like AERONET, in coincidence as close as possible, both in time and in position. How close in time and space is close enough? A first difficulty is the spatio-temporal collocations of the two types of measurements (Ichoku et al., 2002b). A second issue is the different data screening by the two instruments. For example, ground-based sunphotometers and satellite instruments screen for clouds differently. The collocation of the two instruments will only occur when both instruments are reporting data. This tells you nothing about the aerosol retrieval from the satellite when the satellite is reporting data but the ground-based instrument is not. Such cases suggest but do not prove cloud contamination in the aerosol retrieval. This is an example of validating the retrieval, but not the product.

Most importantly, the only quantity directly obtained by ground based instruments, is the aerosol total optical depth, as measured by well calibrated sunphotometers. All other quantities (size distribution, information on sphericity, single scattering albedo, etc.) are actually retrieved from measurements, by algorithms, which are neither simpler nor more trustable, than the algorithms used for space borne instruments. It is therefore more sensible to speak of «intercomparison» between instruments, than of real validation.

Intercomparison can be performed between different space borne instruments, as well. Here there is again the problem of coincidence of the observations and differences in data screening. For example, Kahn et al. (2009) compare MISR and MODIS products. They find that MISR and MODIS each make successful aerosol retrievals about 15% of the time, discarding a majority of retrieval opportunities because of the presence of clouds, inappropriate surface conditions, etc. However, each sensor chooses a different 15%, collocating for only 6-7% of the total overlapping possibilities.

A third type of intercomparison is between remote sensing data and corresponding in situ measurements. Here the challenge is the comparison between ambient and often total column measurements with samples of particles disturbed from ambient conditions, taken from the partial column. All the issues with spatio-temporal collocations and different screening procedures remain. Still, in situ measurements can get to the heart of the particle properties and provide both a constraint when these properties are retrieved and on the assumptions inherent in the retrievals when the particle properties are assumed.

Another promising approach to validating algorithms has been proposed by Kokhanovsky et al. (2010), and relies on using synthetic data. Starting with an aerosol model, a forward calculation is made to produce the entire suite of reflectances and polarized radiances (if applicable) that would be measured by each sensor. This output is computed for each wavelength and view angle of the sensor in question. Then these properties are inverted using the instrument's operational inversion algorithm. The retrieved quantities are compared with the original aerosol model parameters. Such a comparison provides important insight into algorithms but not products. The comparison is highly theoretical, not accounting for retrievals tuned for the real world through empirical assumptions. Also such an exercise does not deal with such real-world retrieval issues as clouds, calibration drift etc.

Validation is an on-going process that requires multiple approaches. It is unrealistic that an aerosol data product can be declared 'validated' and used indiscriminantly for the remainder of the satellite mission. Even if the retrieval algorithms were frozen in time, the sensors are not. Satellite sensor calibration can and does drift in time, which makes long-term trend studies such as shown in Figure 7-4 very difficult to interpret (Zhang and Reid, 2010).

11.4 Recommendations for future work

The priority of any future work is to continue to maintain the capability that we have today. We need continuation of the satellite product records for as long the sensors are operating and on orbit, and we need the continuation of the complementary suite of suborbital networks and airborne sensors to serve as a source of validation and intercomparison. These data records require continual evaluation and examination for changing calibration and refinements of the algorithms.

As sensors age and the data stream ends, new sensors need to be launched. Rather than being carbon copies of existing sensors we should push technology forward and enhance the capability of future aerosol space missions. Increasing spectral range, decreasing pixel size, enhancing angular views and adding polarization provides new information for more comprehensive retrievals that provide a more complete characterization of the aerosol system. Expanding space-based lidar from current backscattering measurements to directly measured extinction profiles offers opportunity for a much clearer 3-dimensional characterization of the global aerosol, including vertical profiles of aerosol absorption properties. A multi-beam or scanning lidar can expand the limited lidar coverage currently available. Adding high temporal resolution from geostationary platforms, expanding oceanic suborbital observations to include sky radiance and inversions, and implementing some of the more advanced and experimental retrieval ideas described in Section 8.8 and Chapter 9, are just some of the innovations that should be possible in the near future.

As new technology is being developed to provide this additional capability, new algorithms must also be generated. The old LUT approach is entirely appropriate when a sensor ingests a small set of inputs that must be constrained with *a priori* assumptions. However, if a sensor is providing multispectral, multiangle, polarization information, there is sufficient information to apply optimal estimation methods without need to overly constrain the retrieval with severe assumptions (Sections 8.5.3 and 8.8). These new algorithms must be in development now in order to meet the challenges of the next generation of sensors.

Even as sensors and algorithms advance, there will always be need to consider associating different sensors and platforms together to make use of complementary information and to be able to intercompare. Section 8.9.5 touches on some of the benefits of combining information from different instruments, and these benefits will continue even as aerosol remote sensing from each particular instrument becomes more sophisticated.

Validation and intercomparison will be a constant need in the future, as it is now. Sensors require intercomparison. Algorithms require intercomparison. Data products require intercomparison. There needs to be more concern for sensor calibration issues, more algorithm intercomparison using synthetic data, more opportunities to compare final products and not just aerosol optical thickness. In situ data should not be ignored because it provides valuable information on the aerosol particles themselves, and as retrievals become more sophisticated and provide more aerosol parameters, in situ characterization of particle properties are the only hope of constraining parameters such as phase function and complex refractive index. Technology development in the realm of in situ sampling must keep up with the technology development of remote sensing instrumentation.

Aerosol observations from remote sensing are playing an increasingly important role in numerical modeling at all scales. Aerosol remote sensing data are used to constrain global climate and regional air quality models, and aerosol products are being operationally assimilated into global-scale forecast models (Section 8.9.5). These hybrid systems that depend on a constant stream of global aerosol information to provide a better representation of the global aerosol system will continue to require daily operational satellite-derived aerosol products.

Finally as the community moves forward, continuity with present data records must be maintained. There should be opportunity for overlapping data sets between old and new sensors. Therefore, there is no time to waste. Examination of the tables in this chapter points out that there is no current occultation instrument to continue the long-term upper atmosphere record. NPP-VIIRS has just been launched to continue the data record from MODIS, but what of the additional capabilities associated with MISR, POLDER, etc.? What happens when CALIOP expires? To maintain a continuous data record, replacement sensors need to be launched before aging sensors die.

The field of aerosol remote sensing has been growing over centuries, but has accelerated greatly over the past 30 years. There is no end in sight. We have not fully exploited the information content available to be measured and interpreted from the interaction between radiation and a dispersion of suspended particles. There is much work left for the future.