Remote Sensing of Spectral Aerosol Properties

A Classroom Experience

BY ROBERT C. LEVY AND RACHEL T. PINKER

The direct and indirect radiative effects of aerosols on climate and climate change remain a source of uncertainty in climate research (Houghton et al. 2001). Aerosols [also known as particulate matter (PM)] play an important role in precipitation processes, reduced visibility, and human morbidity (Samet et al. 2000). Before the satellite era, information on aerosols came from limited surface-based observations, which are not sufficient to describe their spatial and temporal variability.

With their vantage high above the Earth, satellite observations of reflected and emitted radiances are increasingly being used to monitor aerosols and their interactions within the climate system (King et al. 1999). A highly successful project is the National Aeronautics and Space Administration's (NASA's) Moderate Resolution Imaging Spectrometer (MODIS; Salomonson et al. 1989), which has been observing from aboard the *Terra* (since 2000) and *Aqua* (since 2002) satellite platforms. By observing spectral radiances in 36 channels (from 0.412 to 14.2 μm, see information online at http://modis.gsfc.nasa.gov) and at resolutions ranging from 250 m to 1 km, MODIS is highly suitable for deriving aerosol properties over the oceans (Tanré et al. 1996, 1997). The MODIS polar geosynchronous orbit is such that most of the globe is covered each day and completely covered every two days, thus providing comprehensive observations. Because the MODIS data are well characterized and easy to access, they are suitable for introducing students to the physics of remote sensing of aerosols.

AFFILIATIONS: LEVY—Science Systems and Applications, Inc., Lanham, Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, Maryland; PINKER—Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, Maryland
CORRESPONDING AUTHOR: Robert Levy, SSAI, Code 613.2, NASA Goddard Space Flight Center, Greenbelt, MD 20771.
E-mail: levy@climate.gsfc.nasa.gov

DOI:10.1175/BAMS-88-1-25

As part of a graduate course in remote sensing, students used MODIS data and focused on the following:

- understanding how aerosols interact with reflected solar radiation,
- obtaining a working knowledge of inversion techniques for retrieving aerosol properties over oceans,
- implementing the MODIS algorithm to retrieve aerosol properties from observations,
- contrasting aerosol properties from different sites and relating them to geography and season, and
- evaluating satellite retrievals in the context of ground-based aerosol measurements.

This paper reviews the basic physics of the remote sensing of aerosols and describes selected findings and lessons learned by the students. Data, codes, and detailed instructions needed to perform the exercises are available online at www.atmos.umd.edu/~levy/MODIS_Aerosol_Project.

REMOTE SENSING OF AEROSOLS OVER THE OCEAN FROM MODIS AND AERONET.

Aerosols are suspended liquids or solids in the atmosphere, ranging in size from a few molecules to tens of micrometers. Aerosols having radii of about 0.1 and 20 μm are of primary interest, where 1.0 μm denotes the approximate separation between "fine" and "coarse" aerosols. The aerosol optical depth (AOD; or τ) defines the integral of the light extinction by aerosols within an atmospheric column. Spectral dependence of τ is related to aerosol size distribution (Eck et al. 1999), and the fine-mode weighting (FMW; or η) describes the contribution of the fine aerosols to the total τ at a specific wavelength (λ). By convention, τ and η are reported for $\lambda = 0.55$ μm.

Sun photometers have been in operation for many years and, when calibrated properly, provide accurate measurements of spectral τ (function of λ; i.e., τ_λ). By accounting for known effects of molecular scattering (Raleigh scattering) and gas absorption, sunphotometer measurements of spectral direct-beam extinction are directly related to τ_λ as expressed by the Beer–Bouger extinction law. The current standard for ground-based sun photometry is the Aerosol Robotic Network (AERONET) (Holben et al. 1998), which provides continuous daytime measurements of τ_λ with an accuracy of ±0.01 at most wavelengths (Remer et al. 2005; Pinker et al. 2001; Eck et al. 2003) at over 100 sites globally.

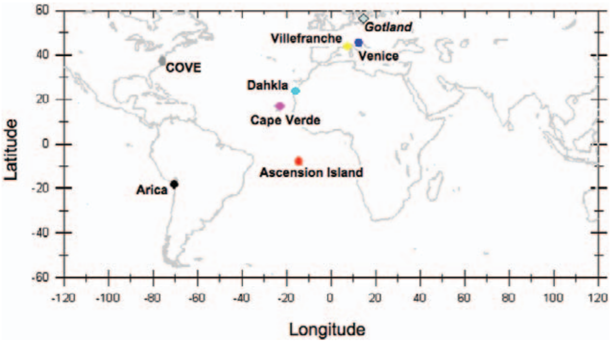

Fig. 1. Map of AERONET sites selected for this study.

Whitby (1978) showed that a series of lognormal size distributions accurately describe aerosol sizes. In most situations, aerosols that interact with solar radiation can be modeled as a weighted combination of two lognormal modes—one for the fine and one for the coarse mode (Wang and Gordon 1994). Theoretically, using radiative transfer codes, one can precompute a lookup table (LUT) of simulated satellite-observed reflectance (normalized radiance) arising from a variety of aerosol conditions for a subset of realistic geometries (satellite and sun angles) and total aerosol loadings τ (Tanré et al. 1997). For MODIS, there are four choices of fine modes and five choices of coarse modes, simulated for 2,304 solar–satellite angle combinations, and seven values of τ indexed by 0.55 μm (Levy et al. 2003; Remer et al. 2005). Note that the actual spectral reflectance for each mode includes contributions from the surface and the molecular atmosphere (Rayleigh scattering).

MODIS aerosol properties over oceans (known as "level 2" products) are retrieved at 10 km × 10 km resolution, meaning that the spectral reflectance values used for the retrieval must be representative of the target area. Remer et al. (2005) describe how the high-resolution (250- and 500-m resolution) MODIS spectral reflectance observations (known as "level 1" data) are aggregated, corrected for gas absorption, and selectively averaged (including glint, cloud, and sediment masking), in order to represent the 10 km × 10 km box. The aerosol retrieval assumes that this level 2 spectral reflectance arises from the radiative effects of a combination of fine and coarse modes within the atmospheric column. The total τ is set to fit the observed reflectance at one wavelength, and η is calculated to match the spectral dependence of τ_λ. Incorrect values of η lead to larger spectral "fitting errors." A separate solution is found for each of the 20 combinations of fine and coarse modes, so that the "best" solution is the one combination of fine (f) and coarse (c) modes with the least fitting error. The spectral AOD (τ_λ) and η are results of the inversion.

Ichoku et al. (2002) developed an algorithm to operationally compare MODIS (level 2) and AERONET products by addressing the issue of spatial and temporal matching. Remer et al. (2002, 2005) used this approach in "validation" of MODIS total τ retrievals over the oceans. Remer et al. (2005) also discuss retrievals of τ_λ and how they relate to retrievals of aerosol size parameters. In our class project, we used

Table 1. MODIS–AERONET collocations used for this project. The first eight sites (normal font) are used in the MODIS–AERONET comparisons. The ninth site (in italic) is used for the manual inversion.

Date	11 Apr 2001	15 Aug 2002	2 Aug 2001	19 Aug 2002	11 Jul 2002	23 Mar 2001	13 Sep 2002	17 Aug 2001	*1 Jan 2002*
Day of year	102	227	215	231	192	83	256	230	*190*
Time (UTC)	1545	1155	1110	1115	930	1145	1115	1525	*1120*
Location	Arica	Ascension Island	Venice #1	Villefranche	Venice #2	Cape Verde	Dahkla	COVE	*Gotland*

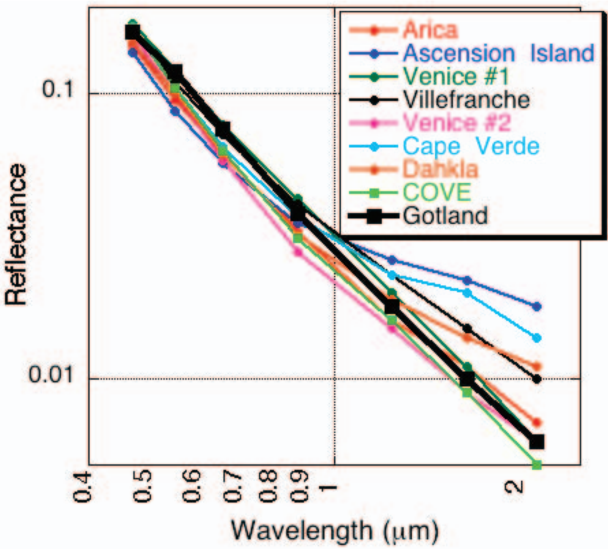

Fig. 2. Plot of reflectance vs wavelength (spectral reflectance) for eight MODIS observations. Data used for the "manual" retrieval (Gotland) are plotted with squares.

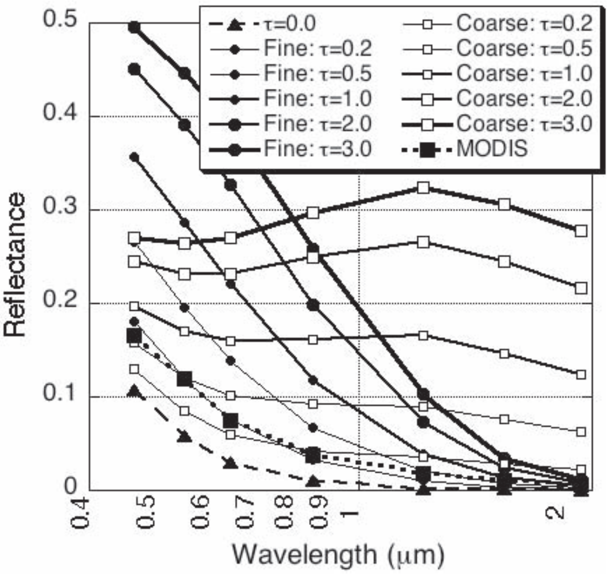

Fig. 3. LUT interpolated to MODIS-observed geometry. Filled circles are the modeled reflectance from the small mode for each of five indexed optical depths (0.2, 0.5, 1.0, 2.0, and 3.0 at 0.55 μm); the open squares are the modeled reflectance arising from the coarse mode. The filled triangles (dashed line) are the modeled Rayleigh reflectance, and the filled squares (dotted line) are the MODIS observation for Gotland. Reflectance from each mode increases monotonically with τ (AOD).

a set of nine MODIS–AERONET collocations in order to understand how the MODIS inversion works, as well as to study the difference between MODIS and AERONET retrievals of τ_λ.

THE CLASS PROJECT. The aerosol inversion, as summarized in a few paragraphs above, is actually quite complicated. It was assumed that students could best understand inversion and the resulting products by performing a simplified inversion "by hand." Students used MODIS (level 2) spectral reflectance as observed over the ocean near coastal and island AERONET sites (Fig. 1) during 2001 and 2002. Coincident AERONET-derived τ_λ data were used to evaluate the MODIS-derived products. In all, nine pairs of collocated MODIS–AERONET data were used for the project (Table 1).

The skills required for this project are familiarity with Fortran compiling and use of "*Y* versus *X*" plotting software. A Fortran source code and data files with instructions for downloading, compiling, and running the programs are provided to the students and are now publicly available (online at www.atmos.umd.edu/~levy/MODIS_Aerosol_Project). The input datasets were formatted for easy import into a spreadsheet program (such as Microsoft Excel).

RESULTS. *Aerosols and spectral radiances.* The students were given *Terra* MODIS (level 2) spectral reflectances at seven channels for each of the eight collocations (first eight columns in Table 1). Figure 2 presents plots of reflectance versus wavelength (spectral reflectance) for the eight MODIS observations. All locations show decreasing reflectance with wavelength, which is primarily attributed to lower-oceanic reflectance and molecular (Rayleigh) scattering at longer wavelengths.

They found that spectral dependence is related to location. Both Ascension Island and Cape Verde have "flatter" spectral dependence than the other sites. Both sites are in the Atlantic Ocean and both (especially Cape Verde) are often in the path of the African dust aerosol (e.g., Propero and Carlson 1972; Tanré et al. 2003). Dust aerosols show lower spectral dependence than other types of aerosols (Eck et al. 1999) because of the larger number of coarse aerosols that scatter in the longer wavelengths. Venice, Italy, and the CERES (Clouds and Earth's Radiant Energy System) Ocean Validation Experiment (COVE) are urbanized areas, and are characterized by urban/industrial aerosols (Remer et al. 1998; Dubovik et al. 2002). Because of the larger fraction of the fine mode

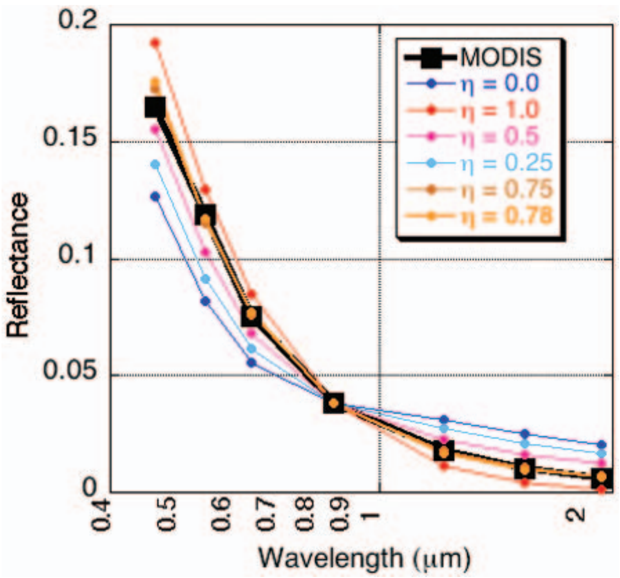

Fig. 4. Reflectance calculated "by hand" (colored circles) vs reflectance observed by MODIS (black squares). Different colors represent different choices of the fine-mode weighting η. The best fit to MODIS data (black squares) arises from η = 0.787 (orange).

in urban aerosols, these sites display larger spectral dependence (Eck et al. 1999).

Hand-calculated aerosol optical depth. This exercise was designed to introduce the students to the MODIS aerosol retrieval algorithm by having them manually perform a MODIS-like inversion. A simplified lookup table was provided for a pair of fine and coarse modes at selected geometries. Also provided was the MODIS spectral reflectance for Gotland (ninth column in Table 1). The students performed the following tasks (analogous to those within the operational algorithm).

As a start they interpolated the entire LUT to the specific solar–surface–satellite geometry measured by MODIS (Fig. 3). This specific-angle LUT was used to fit the observed spectral reflectance. This fitting was done by "halving" the iteration on η, coincident with interpolation on the indexed total τ within the LUT. For the first iteration, they attempted to match the satellite reflectance by assuming that the aerosol was only coarse mode (i.e., $\eta = 0.0$). This resulted in a total τ (at 0.55 μm) of about 0.19, with large differences (fitting errors) between the calculated and observed spectral reflectance (Fig. 4). Assuming only fine-mode aerosol ($\eta = 1.0$) led to lower fitting errors. Trying a half fine and half coarse composition ($\eta = 0.5$) showed significant improvement, while halving again ($\eta = 0.75$) resulted in an even better match with observations. Following Tanré et al. (1996), the process was considered complete after 10 iterations and when the simulated reflectance was within 3% of the observations (Fig. 5). In the case at hand, convergence was achieved after three to four iterations. The accepted solution was estimated to be $\eta = 0.79$ and $\tau = 0.22$ (at 0.55 μm), with a fitting error ε of about 2.5%, but depended on how the students chose to handle significant digits in their calculations.

Global aerosol retrievals and comparison with sun photometer data. How do aerosol properties vary globally? The students were given instructions for compiling and running a stand-alone version of the operational MODIS algorithm (also available from the listed Web sites). Using MODIS angle and reflectance data described in "Aerosols and spectral radiances" as input, the aerosol optical properties were retrieved for each case. Figure 6 compares the spectral dependence of τ_λ retrieved from both MODIS and AERONET at eight sites.

The spectral dependence of τ was seen to resemble the observed spectral dependence of the reflectance for each location. This reflects the characteristics of the aerosols near each site. As expected, the spectral dependence of τ_λ is smaller (flatter) for dusty or midocean sites (Ascension Island, Cape Verde) than for more polluted (urban/industrial or smoke aerosol) sites near coastlines (COVE, Venice). Af-

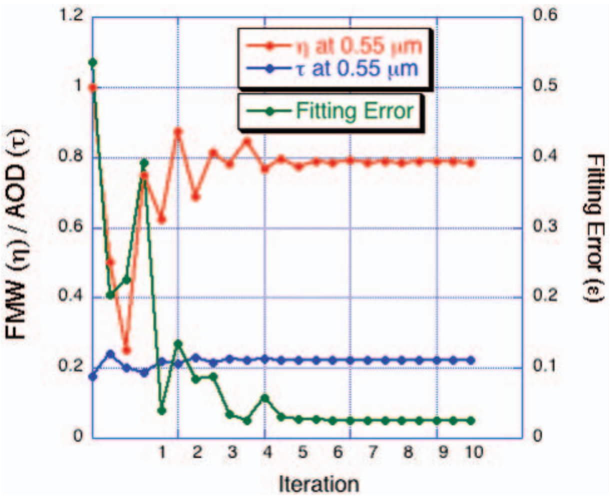

Fig. 5. Fitting error (green), fine-mode weighting (red), and aerosol optical depth (blue) calculated at each iteration of the MODIS retrieval.

rica shows a combination of small (presumably smoke) and larger sea salt aerosols. The retrieval of η mirrors the spectral dependence of τ_λ, with the larger particles over Ascension Island and Cape Verde and the smaller particles over COVE and Venice. These results are consistent with what is known about aerosol characteristics in these regions.

Figure 6 shows good visual agreements for Venice (1); Villefranche, France; and COVE. These three sites are from regions known to be dominated by fine-mode aerosols, and the spherical aerosol assumption (Mie theory) is appropriate. On the other hand, for regions dominated by larger, nonspherical dust particles, the differences between the two products are considerable (e.g., at Ascension Island and Dahkla, Morocco). This implies that the aerosol models employed in the MODIS algorithm are not sufficient for describing the ambient aerosol properties at these sites (e.g., Levy et al. 2003). Interestingly, the differences between the MODIS and AERONET retrievals for regions with large aerosols tend to increase with increasing wavelength, while those for regions with small aerosols tend to increase with decreasing wavelength.

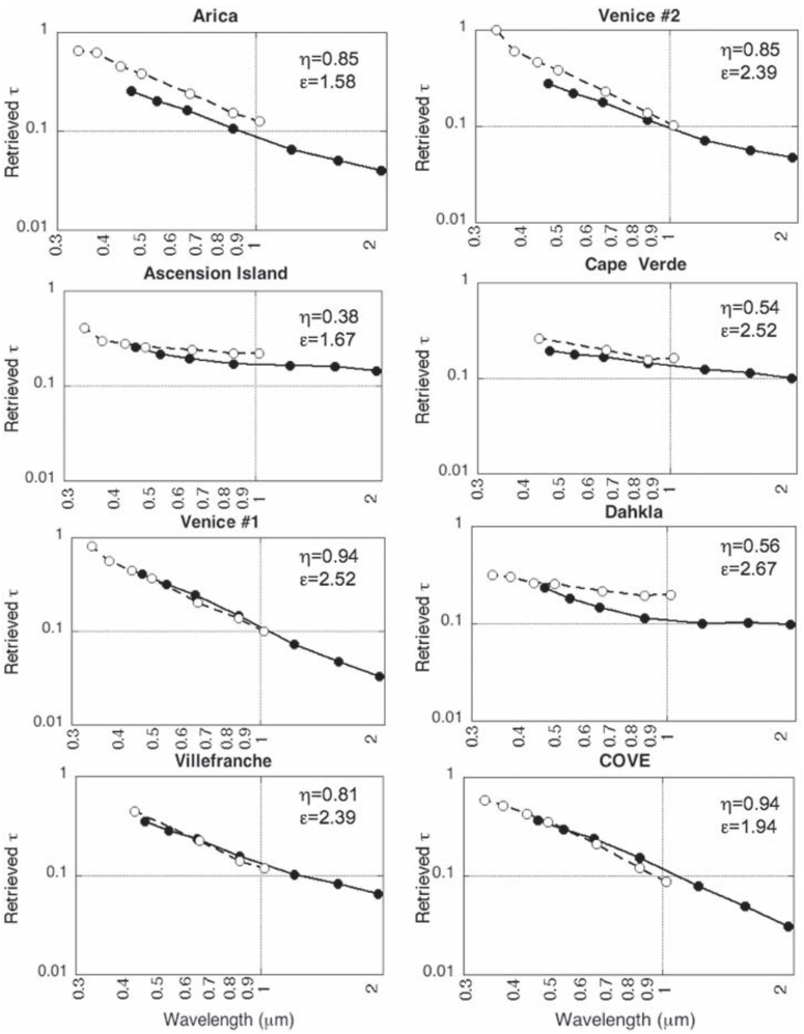

Fig. 6. Spectral τ_λ retrieved by MODIS (solid) and AERONET (dashed) for each location. MODIS-retrieved η and fitting error are indicated on each plot.

SUMMARY AND CONCLUSIONS. The objective of this project was to expose graduate students to current research in aerosol remote sensing. The students learned about the spectral dependence of aerosol scattering and how it is exploited in the MODIS aerosol retrieval algorithm to estimate aerosol optical properties.

Because of the importance of aerosols in atmospheric radiative processes and their climatic implications, the project is relevant to interdisciplinary problems. Moreover, MODIS represents state-of-the-art science and technology for the remote sensing of several earth–atmosphere processes. MODIS, as well as other satellite data are free, easily available, and increasingly useful in many applications, so there is a great need to learn how to process such data and interpret them in new and exciting ways. Projects such as this provide an opportunity for students and young scientists to become familiar with (and less apprehensive of) datasets of this magnitude.

ACKNOWLEDGMENTS. At the time of project development, Robert Levy was a student in Rachel Pinker's Remote Sensing class (METO624) in the Department of Atmospheric and Oceanic Science, University of Maryland. Five other students performed the tasks of this project (Hiroko Kato, Myeong-Jae Jeong, Ruiming Chen, Fan Lei, and Hengmao Wang). Their figures have been recreated here for consistency. We thank Lorraine Remer and the late Yoram Kaufman for contributing to the development of the idea for this project and Shana Mattoo for her help with the development of the computer code. Support under NASA grant NNG04GD65G from the Office of Earth Sciences to the University of Maryland is appreciated.

REFERENCES

Dubovik, O., and M. D. King, 2000: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements. *J. Geophys. Res.,* **105** (D16), 20 673–20 696.

——, B. Holben, T. F. Eck, A. Smirnov, Y. J. Kaufman, M. D. King, D. Tanré, and I. Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *J. Atmos. Sci.,* **59,** 590–608.

Eck, T. F., B. N. Holben, J. S. Reid, O. Dubovik, A. Smirnov, N. T. O'Neill, I. Slutsker, and S. Kinne, 1999: Wavelength dependence of the optical depth of biomass burning, urban and desert dust aerosols. *J. Geophys. Res.,* **104** (D8) 31 333–31 349.

——, and Coauthors, 2003: Variability of biomass burning aerosol optical characteristics in southern Africa during the SAFARI 2000 dry season campaign and a comparison of single scattering albedo estimates from radiometric measurements. *J. Geophys. Res.,* **108,** 8477, doi:10.1029/2002JD002321.

Holben, B. N., and Coauthors, 1998: AERONET - A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.,* **66,** 1–16.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu, Eds., 2001: *Climate Change 2001: The Scientific Basis.* Cambridge University Press, 944 pp.

Ichoku, C., D. A. Chu, S. Mattoo, Y. J. Kaufman, L. A. Remer, D. Tanré, I. Slutsker, and B. N. Holben, 2002: A spatio-temporal approach for global validation and analysis of MODIS aerosol products. *Geophys. Res. Lett.,* **29,** 8006, doi:10.1029/2001GL013206.

Kaufman, Y. J., D. Tanrè, and O. Boucher, 2002: A satellite view of aerosols in the climate system. *Nature,* **419,** 215–223.

King, M. D., Y. J. Kaufman, D. Tanré, and T. Nakajima, 1999: Remote sensing of tropospheric aerosols from space: Past, present and future. *Bull. Amer. Meteor. Soc.,* **80,** 2229–2259.

Levy, R. C., L. A. Remer, D. Tanré, Y. J. Kaufman, C. Ichoku, B. N. Holben, J. M. Livingston, P. B. Russell, and H. Maring, 2003: Evaluation of the Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals of dust aerosol over the ocean during PRIDE. *J. Geophys. Res.,* **108,** 8594, doi:10.1029/2002JD002460.

Pinker, R. T., G. Pandithurai, B. N. Holben, O. Dubovik, and T. O. Aro, 2001: A dust outbreak episode in sub-Sahel West Africa. *J. Geophys. Res.,* **106** (D19) 22 923–22 930.

Prospero, J. M., and T. N. Carlson, 1972: Vertical and areal distribution of Saharan dust over the western equatorial north Atlantic Ocean. *J. Geophys. Res.,* **77,** 5255–5265.

Remer, L. A., and Y. J. Kaufman, 1998: Dynamical aerosol model for urban/industrial aerosol. *J. Geophys. Res.,* **103,** 13 859-13 871.

——, and Coauthors, 2002: Validation of MODIS aerosol retrieval over ocean. *Geophys. Res. Lett.,* **29,** 8008, doi:10.1029/2001GL013204.

——, and Coauthors, 2005: The MODIS aerosol algorithm, products and validation. *J. Atmos. Sci.,* **62,** 947–973.

Salomonson, V. V., W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow, 1989: MODIS: Advanced facility instrument for studies of the Earth as a system. *IEEE Trans. Geosci. Remote Sens.,* **27,** 145–153.

Samet, J. M., F. Dominici, F. C. Curriero, 2000: Fine particulate air pollution and mortality in 20 US cities, 1987–1994. *New England J. Medicine,* **343**(24), 1742–1749.

Tanré, D., M. Herman, and Y. J. Kaufman, 1996: Information on aerosol size distribution contained in solar reflected spectral radiances. *J. Geophys. Res.,* **101** (D14), 19 043–19 060.

——, Y. J. Kaufman, M. Herman, and S. Mattoo, 1997: Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances. *J. Geophys. Res.,* **102** (D14), 16 971–16 988.

——, and Coauthors, 2003: Measurement and modeling of the Saharan dust radiative impact: Overview of the Saharan Dust Experiment (SHADE). *J. Geophys. Res., 108,* 8574, doi:10.1029/2002JD003273.

Wang, M., and H. R. Gordon, 1994: Radiance reflected from the ocean-atmosphere system: Synthesis from individual components of the aerosols size distribution. *Appl. Opt.,* **33,** 7088–7095.

Whitby, K. Y., 1978: The physical characteristics of sulfur aerosols. *Atmos. Environ.,* **12,** 135–159.