

This discussion paper is/has been under review for the journal Atmospheric Measurement Techniques (AMT). Please refer to the corresponding final paper in AMT if available.

Aerosol optical depth and fine-mode fraction retrieval over East Asia using multi-angular total and polarized remote sensing

T. Cheng, X. Gu, D. Xie, Z. Li, T. Yu, and H. Chen

State Key Laboratory of Remote Sensing Science, Jointly Sponsored by the Institute of Remote Sensing Applications of Chinese Academy of Sciences and Beijing Normal University, Beijing, China

Received: 2 July 2011 – Accepted: 5 September 2011 – Published: 8 September 2011

Correspondence to: T. Cheng (cthy@irsa.ac.cn)

Published by Copernicus Publications on behalf of the European Geosciences Union.

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

A new aerosol retrieval algorithm using multi-angular total and polarized measurements is presented. The algorithm retrieves aerosol optical depth (AOD), fine-mode fraction (FMF) for studying the impact of aerosol on climate change. The retrieval algorithm is based on a lookup table (LUT) method, which assumes that one fine and one coarse lognormal aerosol modes can be combined with proper weightings to represent the ambient aerosol properties. To reduce the ambiguity in retrieval algorithm, the key characteristics of aerosol model over East Asia are constrained using the cluster analysis technique based on the AERONET sun-photometer observation over East Asia. A mixing model of bare soil and green vegetation spectra and the Nadal and Breon model for the bidirectional polarized reflectance factor (BPDF) were used to simulate total and polarized surface reflectance of East Asia. By applying the present algorithm to POLDER measurements, three different aerosol cases of clear, polluted and dust are analyzed to test the algorithm. The comparison of retrieved aerosol optical depth (AOD) and fine-mode fraction (FMF) with those of AERONET sun-photometer observations show reliable results. Preliminary validation is encouraging. Using the new aerosol retrieval algorithm for multi-angular total and polarized measurements, the spatial and temporal variability of anthropogenic aerosol optical properties over East Asia, which were observed during a heavy polluted event, were analyzed. Exceptionally high values of aerosol optical depth contributed by fine mode of up to 0.5 (at 0.865 μm), and high values of fine-mode fraction of up to 0.9, were observed in this case study.

1 Introduction

The impact of aerosol on climate change is considered as one of the main uncertainties in climate modeling, which has led to large efforts for improving their global monitoring (Anderson et al., 2003; Andreae et al., 2005; Charlson et al., 1969; IPCC, 2007). Climate change research requires knowledge of anthropogenic component of aerosol,

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Aerosol optical depth
and fine-mode
fraction retrieval**

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



which can be considered as an external cause of climate change (Charlson et al., 1992; Hansen et al., 1997). To obtain an estimate of aerosol direct radiative forcing (DRF), a measure of the anthropogenic aerosol loading and knowledge of their size distributions and refractive indices are needed (Hansen et al., 1998; Haywood and Boucher, 2005; Bellouin et al., 2005).

Even though the significance of aerosol in climate change is well recognized and several efforts have been made to model their characteristics, there exist large uncertainties (Kaufman et al., 2002; Costa et al., 2004; Bellouin et al., 2008). One of the greatest challenges in studying aerosol impacts on climate is the immense diversity, not only aerosol size, composition, and origin, but also in spatial and temporal distribution (Bates et al., 2001; Dubovik et al., 2002, 2008). One consequence of this heterogeneity is that the impact of aerosol on climate change must be understood and quantified on a regional rather than just a global-average basis (Delene and Ogren, 2002; Mishchenko and Geogdzhayev, 2007).

Yet most assessments of aerosol DRF are based only on climate models since satellite instruments do not directly measure the anthropogenic aerosol properties. Although models are compared and validated against observations, their estimates of aerosol DRF remain uncertain (Chin et al., 2002). Kaufman et al. (2005) estimated aerosol anthropogenic component over ocean from MODIS measurements, which use the aerosol optical depth and the fine-mode fraction of aerosol over ocean to derive the anthropogenic optical depth.

The fine-mode fraction of aerosol retrieved by satellite is unfortunately not considered reliable over land surfaces (Anderson et al., 2005, 2006), where the main aerosol sources are located, because of the difficulty in discriminating the aerosol contribution from the ground in top of the atmosphere measurements (Diner et al., 2005; Hauser et al., 2005; Kokhanovsky et al., 2007, 2010; Mishchenko and Geogdzhayev, 2007). The multi-angle polarized measurements provide an alternative and robust approach for the study of aerosols over land (Deuzé et al., 2001; Chowdhary et al., 2005; Hasekamp and Landgraf, 2005, 2007; Cheng et al., 2011). Indeed the polarized surface contribution

**Aerosol optical depth
and fine-mode
fraction retrieval**

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2 Aerosol retrieval algorithm

2.1 Aerosol optical depth and fine-mode fraction retrieval scheme

The important advantage of the multi-angular, multi-spectral, total and polarized radiation measurements enables us to retrieve aerosol optical depth with size information simultaneously. The two main aerosol parameters (AOD and FMF) were simultaneously retrieved using POLDER measurements (Deschamps et al., 1994) in this paper.

The atmosphere-surface system is assumed as plane parallel, so the optical properties of atmosphere and surface depend only on the vertical coordinate (Hansen and Travis, 1974). A vector radiative transfer model is used with the corresponding geometry ($\theta_s, \theta_v, \varphi$) for the given aerosol optical depth, aerosol optical properties (single scattering albedo, asymmetry parameter). In this study, the RT3 vector radiative transfer mode (Evans and Stephens, 1991) is used, which simulates radiation fields in the atmosphere-land system assuming plane parallel atmosphere.

A lookup tables (LUT) approach is adopted to retrieve AOD and FMF. The LUT are constructed based on extensive analysis of aerosol optical properties obtained from AERONET sun-photometer observations (Holben et al., 1998,).

The algorithm of this paper assumes that one fine and one coarse lognormal aerosol modes can be combined with proper weightings to represent the ambient aerosol properties (Remer et al., 2005). There are six fine modes and six coarse modes in the algorithm. In order to improve the accuracy of aerosol retrieval using remote sensing, the fine and coarse aerosol mode size distribution are determined based on extensive analysis of aerosol optical properties obtained from AERONET sun-photometer observations (Dubovik and King, 2000) over East Asia.

The inversion is based on determining which of the 36 combinations of fine and coarse aerosol models and their relative optical contributions best mimics the TOA spectral polarized measurements. The total and polarized reflectance from each mode

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is combined as follows:

$$R^{\text{LUT}}(\tau, \theta_s, \theta_v, \varphi_r) = \text{FMF} \cdot R^{\text{fine}}(\tau, \theta_s, \theta_v, \varphi_r) + (1 - \text{FMF}) \cdot R^{\text{coarse}}(\tau, \theta_s, \theta_v, \varphi_r) \quad (1)$$

where $R^{\text{LUT}}(\tau, \theta_s, \theta_v, \varphi_r)$ is the weighted average total and polarized reflectance of an atmosphere with a pure fine mode and optical depth and the total and polarized reflectance of an atmosphere with a pure coarse mode with the same optical depth.

The dimensions of calculated LUT are summarized in Table 1.

Figure 1 represents the flowchart of POLDER algorithm to simultaneously retrieve aerosol optical properties. In the algorithm, cloud pixels are detected and masked out first since the accuracy of aerosol properties retrievals is subject to cloud masking due to its strong signal. To determine clear sky pixels and heavy aerosol plumes, cloud pixels were filtered out using the POLDER clear sky discrimination method (Bréon, and Colzy, 1999), which used relaxed threshold value and the 3×3 pixel technique or inhomogeneous cloud detection.

From the LUT of total reflectance, TOA reflectance at $0.490 \mu\text{m}$, and surface reflectance contribution, the initial total AOD is retrieved using the least mean squares fitting method. After that, the initial total AOD, LUT of polarized reflectance, TOA polarized reflectance at $0.675 \mu\text{m}$, $0.870 \mu\text{m}$, and surface polarized reflectance contribution are used to retrieve the FMF for combination of fine- and coarse-mode, and the adjusted Total AOD.

The retrieval algorithm employs the least mean squares fitting method in the form of a series of numerical iteration procedures to search for the computed total and polarization reflectance that best match the measured total and polarized reflectance. The residual term is defined as:

$$\chi = \sum_{w=1}^3 \sum_{n=1}^{16} [R_{\text{comp}}(\lambda_l, \text{AOD}, \text{FMF}, \mu_s, \mu_v, \Delta\phi) - R_{\text{meas}}(\lambda_l, \text{AOD}, \text{FMF}, \mu_s, \mu_v, \Delta\phi)]^2 \quad (2)$$

where w is the number of spectral bands, n is the scattering angle observations for each pixel. R_{comp} and R_{meas} are computed and measured total and polarized

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



reflectance, respectively. μ_s is the cosine of solar zenith angle, μ_v is the cosine of view zenith angle, and $\Delta\phi$ is the relative azimuth angle, respectively.

2.2 Aerosol models over East Asia

Aerosols with different properties originate from various sources: sea-salt particles, desert dust, biomass burning and industrial combustions. Aerosols are characterized by their shape, their size, their chemical composition and total amount, which in turn determine their radiative properties. In a good approximation, the optical properties of a particle are determined by the refractive index and size distribution. The refractive index depends on the chemical composition of the particles.

Lee and Kim have studied (2010) the aerosol models using the cluster analysis technique (Omar et al., 2005) based on the AERONET sun-photometer observation over the East Asia. They defined six aerosol optical modes with the bimodal lognormal size distribution. Each aerosol model has somewhat different values of refractive index at particular wavelengths, median particles radius, and standard deviation of size distribution. The six cluster aerosol models of East Asia can represent realistic possibilities of the aerosol properties.

The aerosol size distribution used in this study for fine and coarse model is the mono-modal lognormal size distribution describes as follows by equation (3),

$$\frac{dV}{d\ln r} = \frac{C}{\sqrt{2\pi} * S} \exp \left[-\frac{(\ln r - \ln Rm)^2}{2(S)^2} \right] \quad (3)$$

where C is the volume concentration, Rm is the particle median radius, S is the standard deviation. The detailed parameters of fine model and coarse model size distribution of the study are retrieved from the six cluster aerosol modes of East Asia, which are described in Table 2.

The complex refractive index and size distributions as given by aerosol models were used to study the scattering properties of aerosol particles (single scattering albedo, asymmetry parameter and the phase matrix). The fine aerosol models are assumed

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



to be spherical particles which can be used Mie model (Wiscombe, 1981) to calculate the scattering properties of the model. The coarse aerosol models are assumed to be spheroids particles which can be used T-matrix code described in Mishchenko et al. (1996, 1998), to calculate the scattering properties of the model.

2.3 Surface reflectance

A precise estimate of the radiation (including polarization of radiation) reflected by the surface is crucial for remote sensing of aerosol properties over land. In this study, over land the surface reflectance is estimated by a mixing model of bare soil and green vegetation spectra, tuned by the normalized differential vegetation index (NDVI) of the satellite scene (von Hoyningen et al., 2003). Thus the method enables the investigation of AOT over land, yielding the regional turbidity situation as well as the identification of aerosol sources like large cities, large fire plumes, haze, small scale dynamical events and also thin cirrus clouds.

Many experimental studies have shown that surface-polarized reflectance is mainly generated by single reflection of incident radiation off surface facets. Based on these observations, the bidirectional polarized reflectance distribution functions (BPDF) of different surface have been developed for vegetation cover and bare soil. The choice of BPDF model is of crucial importance because land surface exhibit a wide variety of architecture and radiative properties. In this study, the experimental model of Nadal and Breon (Nadal and Breon, 1999) – (based on NDVI classification) was used to estimate the polarized reflectance in study region.

3 Retrieval results

To evaluate the performance of the developed algorithm, three different aerosol cases are selected, and retrieval of aerosol optical depth and fine-mode fraction is performed by using TOA multi-angular, multi-spectral, total and polarized measurements.

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Figures 2–4 show the false-color images captured by the POLDER on PARASOL satellite, AOD, and FMF from the developed algorithm on 20 March, 6 October, and 25 October in 2010, respectively.

Figure 2 shows dust case on 20 March, 2010 with thick yellowish aerosol layer in the false-color image. The AOD at $0.870\ \mu\text{m}$ increases over 1.0, and the FMF ranges from 0.2 to 0.3 inferring mixed cases dominate with coarse-mode. Figure 3 shows the thick aerosol layer with AOD over 1.0 is observed over North China Plain with grayish and brownish color in false-color image. The FMF ranges from 0.6 to 0.9 representing the dominance of fine mode aerosol. Figure 4 shows the thin aerosol layer with AOD about 0.2 and FMF about 0.6 inferring mixed cases. From Figs. 2–4, we can see the spatial variability distribution of the three different cases in Northeast China.

4 Analysis and validation

It is essential to have highly accurate ground-based measurements to evaluate the aerosol optical properties derived using satellite remote sensing. To validate the algorithm of aerosol retrievals, the results (Total AOD and FMF) were compared to AERONET sun-photometer measurements (Kleidman et al., 2005). A useful ground measurement needs the following conditions to be met: approximate simultaneity between satellites overpass and sun-photometer measurements (30 min before and after the overpass of the sensor), cloudless conditions and good quality sun photometer data.

To estimate the accuracy of retrieved AOD, and FMF from the POLDER measurements, comparison with AERONET sun-photometer observations in Beijing and Xi'an are shown in Figs. 5–6, respectively.

The retrieval AOD and FMF are in good agreement with that from the ground based sun photometer measurements. This preliminary validation is encouraging. However, the limited number of cases makes that further more comprehensive validations are needed.

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 Application

To evaluate the performance of the developed algorithm, a polluted aerosol event over East Asia, which is observed on 15–22 November 2010, is selected. East Asia is affected by aerosols with different optical properties from fine- to coarse mode. The retrieval of AOD and FMF is performed using TOA multi-angle total and polarized reflectance from POLDER onboard PARASOL satellite.

Fig.7 shows the false-color images captured by the POLDER on PARASOL satellite over the East Asia during 15–22 November 2010. The thickest of the gray-brown aerosols conforms to the North China Plain and the mountain landscape to its south, obscuring the coastlines of Bo Hai and the Yellow Sea. The featureless gray-brown aerosols are so thick that the ground is not visible in parts of the North China Plain.

The fine-mode fraction (FMF), and aerosol optical depth contributed by fine mode (Fine AOD) retrieved using Total AOD and FMF, are shown in Figs. 8–9, respectively, except for the 19 November, and 21 November due to the cloud contaminated.

From Fig.8, we can see that the FMF increased from 0.4 on 15 November to 1.0 on 18 November, and then decreased from 0.9 on 20 November to 0.4 on 22 November. From Fig. 9, we can see that the Fine AOD increased from 0.1 on 15 November to 0.5 on 18 November, and then decreased from 0.3 on 20 November to 0.1 on 22 November. Figures 8 and 9 show the development of a polluted aerosol event during the 15–22 November 2010.

6 Conclusions

The regional climate change of East Asia is affected by aerosols not only their large amount but also with different optical properties from fine mode to coarse mode causing different impacts. To obtain the regional climate effect of aerosol over East Asia, a measure of the anthropogenic aerosol optical properties are needed.

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The main scientific objective of this paper aims to prospects the possibility of simultaneously retrieving the aerosol optical depth, and fine-mode fraction (FMF) over the East Asia using multi-angular, multi-spectral, total and polarized remote sensing measurements, in order to study the anthropogenic aerosol optical properties over East Asia.

A new aerosol retrieval algorithm using multi-angular total and polarized measurements is presented. The algorithm retrieves aerosol optical depth (AOD), fine-mode fraction (FMF) for studying the impact of aerosol on climate change. The retrieval algorithm is based on a lookup table (LUT) which is a function of aerosol optical depth, aerosol optical model (complex with fine mode and coarse mode), surface reflectance model, and viewing and illumination geometries. The information of aerosol models determined using the cluster analysis technique based on the AERONET sun-photometer observation over East Asia. The fine aerosol models are assumed to be spherical particles which can be used Mie model to calculate the scattering properties, while the coarse aerosol models are assumed to be spheroids particles which can be used T-matrix code to calculate the scattering properties. A mixing model of bare soil and green vegetation spectra and the Nadal and Breon model for the bidirectional polarized reflectance factor (BPDF) were used to simulate total and polarized surface reflectance of East Asia.

By applying the present algorithm to POLDER measurements, three different aerosol cases of clear, polluted and dust are analyzed to test the algorithm. The comparison of retrieved aerosol optical depth (AOD) and fine-mode fraction (FMF) with those of AERONET sun-photometer observations show reliable results. Preliminary validation is encouraging. Using the new aerosol retrieval algorithm for multi-angular total and polarized measurements, the spatial and temporal variability of anthropogenic aerosol optical properties over East Asia, which were observed during a heavy polluted event, were analyzed.

The proposed algorithm for retrieving the anthropogenic aerosols optical properties using multi-angular total and polarized measurements has demonstrated its potential

for studying the climate effect of aerosol. However, the limited cases examined so far make comparison difficult, and further validations are needed.

Acknowledgements. This research was supported by the National Basic Research Program of China (973 Program) (Grant No: 2010CB950800), the Funds of the Chinese Academy of Sciences for Key Topics in Innovation Engineering (Grant No: KZCX2-EW-QN311), and the National Natural Science Foundation of China (Grant No: 41001207). The authors thank the ICARE Data and Services Center for providing access to the PARASOL data and for general assistance. We also thank the AERONET PIs Hongbin Chen and Philippe Goloub for their effort in establishing and maintaining the Beijing and Xianghe sites.

References

- Andreae, M. O., Jones, C. D., and Cox, P. M.: Strong present-day aerosol cooling implies a hot future, *Nature*, 435, 1187–1190, doi:10.1038/nature03671, 2005.
- Anderson, T., Charlson, R., Schwartz, S., Knutti, R., Boucher O., Rodhe, H., and Heintzenberg, J.: Climate forcing by aerosols – A hazy picture, *Science*, 300, 1103–1104, 2003.
- Anderson, T., Charlson, R., Bellouin, N., Boucher, O., Chin, M., Christopher, S., Haywood, J., Kaufman, Y., Kinne, S., Ogren, J., Remer, L., Takemura, T., Tanré, D., Torres, O., Trepte, C., Wielicki, B., Winker, D., and Yu, H.: An "A-Train" strategy for quantifying direct aerosol forcing of climate, *B. Am. Meteorol. Soc.*, 86, 1795–1809, 2005.
- Anderson, T. L., Wu, Y., Chu, D. A., Schmid, B., Redemann, J., and Dubovik, O.: Testing the MODIS satellite retrieval of aerosol fine-mode fraction, *J. Geophys. Res.*, 110, D18204, doi:10.1029/2005JD005978, 2006.
- Bates, T. S., Quinn, P. K., Coffman, D. J., Johnson, J. E., Miller, T. L., Covert, D. S., Wiedensohler, A., Leinert, S., Nowak, A., and Neusüb, C.: Regional physical and chemical properties of the marine boundary layer aerosol across the Atlantic during Aerosols99: An overview, *J. Geophys. Res.*, 106, 20767–20782, 2001.
- Bellouin, N., Boucher, O., Haywood, J., and Reddy, M.: Global estimates of aerosol direct radiative forcing from satellite measurements, *Nature*, 438, 1138–1140, doi:10.1038/nature04348, 2005.
- Bellouin, N., Jones, A., Haywood, J., and Christopher, S. A.: Updated estimate of aerosol

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- direct radiative forcing from satellite observations and comparison against the Hadley Centre climate model, *J. Geophys. Res.*, 113, D10205, doi:10.1029/2007JD009385, 2008.
- Bréon, F.-M. and Colzy, S.: Cloud Detection from the Spaceborne POLDER Instrument and Validation against Surface Synoptic Observations, *J. Atmos. Sci.*, 38, 777–785, 1999.
- 5 Charlson, R. J. and Pilat, M.: Climate: The influence of aerosols, *J. Appl. Meteorol.*, 8, 1001–1002, 1969.
- Charlson, R. J., Schwartz, S. E., Hales, J. M., Cess, R. D., Coakley, J. A., Hansen, Jr., J. E., and Hoffman, D. J.: Climate forcing by anthropogenic aerosols, *Science*, 255, 423–430, 1992.
- Cheng, T. H., Gu, X. F., Yu, T., and Tian, G. L.: The reflection and polarization properties of non-spherical aerosol particles, *J. Quant. Spec. Ra.*, 111(6), 895–906, 2010.
- 10 Cheng, T., Gu, X., Xie, D., Li, Z., Yu, T., and Chen, X.: Simultaneous retrieval of aerosol optical properties over the Pearl River Delta, China using multi-angular, multi-spectral, and polarized measurements, *Remote Sens. Environ.*, 115, 1643–1652, 2011.
- Chin, M., Ginoux, P., Kinne, S., Holben, B. N., Duncan, B. N., Martin, R. V., Logan, J. A., Higurashi, A., and Nakajima, T.: Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and sunphotometer measurements, *J. Atmos. Sci.*, 59, 461–483, 2002.
- 15 Chowdhary, J., Cairns, B., Mishchenko, M. I., Hobbs, P. V., Cota, G. F., Redemann, J., Rutledge, K., Holben, B. N., and Russell, E.: Retrieval of aerosol scattering and absorption properties from photopolarimetric observations over the ocean during the CLAMS experiment, *J. Atmos. Sci.*, 62, 1093–1117, 2005.
- Costa, M., Silva, A., and Levizzani, V.: Aerosol characterization and direct radiative forcing assessment over the ocean. Part I: Methodology and sensitivity analysis, *J. Appl. Meteorol.*, 43, 1799–1817, 2004.
- 20 Delene, D. and Ogren, J.: Variability of aerosol optical properties at four North American surface monitoring sites, *J. Atmos. Sci.*, 59, 1135–1150, 2002.
- Deschamps, P. Y., Bréon, F.-M., Leroy, M., Podaire, A., Bricaud, A., Buriez, J. C., and Seze, G.: The POLDER mission: Instrument characteristics and scientific objectives, *IEEE T. Geosci. Remote Sens.*, 32, 598–615, 1994.
- 25 Deuzé, J. L., Bréon, F. M., Devaux, C., Goloub, P., Herman, M., Lafrance, B., Maignan, F., Marchand, A., Nadal, F., Perry, G., and Tanre, D.: Remote sensing of aerosols over land surfaces from POLDER-ADEOS-1 polarized measurements, *J. Geophys. Res.*, 106, 4913–4926, 2001.
- 30

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Diner, D. J., Martonchik, J. V., Kahn, R. A., Pinty, B., Gobron, N., Nelson, D.L., and Holben, B. N.: Using angular and spectral shape similarity constraints to improve MISR aerosol and surface retrievals over land, *Remote Sens. Environ.*, 94, 155–171, 2005.

Dubovik, O. and King, M. D.: A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements, *J. Geophys. Res.*, 105, 20673–20696, 2000.

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

Dubovik, O., Lapyonok, T., Kaufman, Y. J., Chin, M., Ginoux, P., Kahn, R. A., and Sinyuk, A.: Retrieving global aerosol sources from satellites using inverse modeling, *Atmos. Chem. Phys.*, 8, 209–250, doi:10.5194/acp-8-209-2008, 2008.

Dubovik, O., Herman, M., Holdak, A., Lapyonok, T., Tanré, D., Deuzé, J. L., Ducos, F., Sinyuk, A., and Lopatin, A.: Statistically optimized inversion algorithm for enhanced retrieval of aerosol properties from spectral multi-angle polarimetric satellite observations, *Atmos. Meas. Tech.*, 4, 975–1018, doi:10.5194/amt-4-975-2011, 2011.

Evans, K. F. and Stephens, G. L.: A New Polarized Atmospheric Radiative Transfer Model, *J. Quant. Spec. Ra.*, 46, 413–23, 1991.

Hansen, J. E. and Travis, L. D.: Light scattering in planetary atmospheres, *Space Sci. Rev.*, 16, 527–610, 1974.

Hansen, J. E., Sato, M., and Ruedy, R.: Radiative forcing and climate response, *J. Geophys. Res.*, 102, 6831–6864, 1997.

Hansen, J. E., Sato, M., Lacis, A., Ruedy, R., Tegen, I., and Matthews, E.: Perspective: Climate forcings in the industrial era, *P. Natl. Acad. Sci.*, 95, 12753–12758, 1998.

Hasekamp, O. P. and Landgraf, J.: Retrieval of aerosol properties over the ocean from multi-spectral single-viewing-angle measurements of intensity and polarization: retrieval approach, information content, and sensitivity study, *J. Geophys. Res.*, 110, D20207, doi:10.1029/2005JD006212, 2005.

Hasekamp, O. P. and Landgraf, J.: Retrieval of aerosol properties over land surfaces: capabilities of multiple-viewing-angle intensity and polarization measurements, *Appl. Opt.*, 46, 3332–3344, 2007.

Hasekamp, O. P., Litvinov, P., and Butz, A.: Aerosol properties over the ocean from PARASOL multiangle photopolarimetric measurements, *J. Geophys. Res.*, 116, D14204,

doi:10.1029/2010JD015469, 2011.

Hauser, A., Oesch, D., Foppa, N., and Wunderle, S.: NOAA AVHRR derived aerosol optical depth over land, *J. Geophys. Res.-Atmos.*, 110.D08204, doi:10.1029/2004JD005439, 2005.

Haywood, J. and Boucher, O.: Estimates of the direct and indirect radiative forcing due to troposphere aerosols: A review, *Rev. Geophys.*, 38, 513–44, 2000.

Holben, N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y.J., Nakajima, T., Lavenu, F., Jankowiak, I. and Smirnov, A.: AERONET- A Federated Instrument Network and Data Archive for Aerosol Characterization, *Remote Sens. Environ.*, 66, 116, 1998.

Intergovernmental Panel on Climate Change (IPCC). Climate Change 2007: The Physical Science Basis, Cambridge University Press, 2007.

Kaufman, Y. J., Tanre, D., and Boucher, O.: A satellite view of aerosols in the climate system, *Nature*, 419, 215–22, 2002.

Kaufman, Y. J., Boucher, O., Tanré, D., Chin, M., Remer, L. A., and Takemura, T.: Aerosol anthropogenic component estimated from satellite data, *Geophys. Res. Lett.*, 32, 4 pp., doi:10.1029/2005GL023125, 2005.

Kleidman, R. G., O'Neill, N. T., Remer, L. A., Kaufman, Y. J., Eck, T. F., Tanre, D., Dubovik, O., and Holben, B. N.: Comparison of Moderate Resolution Imaging Spectroradiometer (MODIS) and Aerosol Robotic Network (AERONET) remote-sensing retrievals of aerosol fine mode fraction over ocean, *J. Geophys. Res.-Atmos.*, 110, D22205, doi:10.1029/2005JD005760, 2005.

Kokhanovsky, A. A., Breon, F.-M., Cacciari, A., Carboni, E., Diner, D., Di Nicolantonio, W., Grainger, R. G., Grey, W. M. F., Höller, R., Lee, K.-H., Li, Z., North, P. R. J., Sayer, A. M., Thomas, G. E., and von Hoyningen-Huene, W.: Aerosol remote sensing over land: A comparison of satellite retrievals using different algorithms and instruments, *Atmos. Res.*, 85, 372–394, 2007.

Kokhanovsky, A. A., Deuzé, J. L., Diner, D. J., Dubovik, O., Ducos, F., Emde, C., Garay, M. J., Grainger, R. G., Heckel, A., Herman, M., Katsev, I. L., Keller, J., Levy, R., North, P. R. J., Prikhach, A. S., Rozanov, V. V., Sayer, A. M., Ota, Y., Tanr, D., Thomas, G. E., and Zege, E. P.: The inter-comparison of major satellite aerosol retrieval algorithms using simulated intensity and polarization characteristics of reflected light, *Atmos. Meas. Tech.*, 3, 909–932, doi:10.5194/amt-3-909-2010, 2010.

Lee, K. H. and Kim, Y. J.: Satellite remote sensing of Asian aerosols: a case study of clean,

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



[Back](#)

Close

Full Screen / Esc

[Printer-friendly Version](#)

Interactive Discussion



polluted, and Asian dust storm days, *Atmos. Meas. Tech.*, 3, 1771–1784, doi:10.5194/amt-3-1771-2010, 2010.

Litvinov, P., Hasekamp, O., Cairns, B., and Mishchenko, M.: Reflection models for soil and vegetation surfaces from multiple viewing angle photopolarimetric measurements, *J. Quant. Spectrosc. Ra.*, 111, 529–539 2010.

Litvinov, P., Hasekamp, O., and Cairns, B.: Models for surface reflection of radiance and polarized radiance: comparison with airborne multi-angle photopolarimetric measurements and implications for modeling top-of-atmosphere measurements, *Remote Sens. Environ.*, 115, 781–792, 2011.

Mishchenko, M. I., Travis, L. D., and Mackowski, D. W.: T-matrix computations of light scattering by nonspherical particles: A review, *J. Quant. Spec. Ra.*, 55, 535–575, 1996.

Mishchenko, M. I. and Travis, L. D.: Satellite retrieval of aerosol properties over the ocean using polarization as well as intensity of reflected sunlight, *J. Geophys. Res.*, 102, 16989–17013, 1997.

Mishchenko, M. I., Travis, L. D.: Capabilities and limitations of a current FORTRAN implementation of the T-matrix method for randomly oriented, rotationally symmetric scatterers, *J. Quant. Spec. Ra.*, 60, 309–324, 1998.

Mishchenko, M. I. and Geogdzhayev, I. V.: Satellite remote sensing reveals regional tropospheric aerosol trends, *Opt. Exp.*, 15, 7423–7438, 2007.

Nadal, F. and Bréon, F. M.: Parameterization of surface polarized reflectance derived from POLDER spaceborne measurements, *IEEE T. Geosci. Remote Sens.*, 37, 1709–1718, 1999.

Omar, A. H., Won, J. G., Winker, D. M., Yoon, S. C., Dubovik, O., and McCormick, M. P.: Development of Global Aerosol Models using Cluster Analysis of AERONET Measurements, *J. Geophys. Res.-Atmos.*, 110, D10S14, doi:10.1029/2004JD004874, 2005.

Remer, L. A., Kaufman, Y. J., Tanré, D., Mattoo, S., Chu, D. A., Martins, J. V., Li, R.-R., Ichoku, C., Levy, R. C., Kleidman, R. G., Eck, T. F., Vermote, E., and Holben, B. N.: The modis aerosol algorithm, products, and validation, *J. Atmos. Sci.*, 62, 947–973, 2005.

Von Hoyningen-Huene, W., Freitag, M., and Burrows, J. B.: Retrieval of aerosol optical thickness over land surfaces from top-of-atmosphere radiance, *J. Geophys. Res.*, 108, 4260, doi:10.1029/2001JD002018, 2003.

Waquet, F., Goloub, P., Deuzé, J. -L., Léon, J.-F., Auriol, F., and Verwaerde, C.: Aerosol retrieval over land using a multiband polarimeter and comparison with path radiance method,

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- J. Geophys. Res., 112, D11214, 2007.
- Waquet, F., Cairns, B., Knobelspiesse, K., Chowdhary, J., Travis, L. D., Schmid, B., and Mishchenko, M. I.: Polarimetric remotesensing of aerosols over land, J. Geophys. Res., 114, D01206, doi:10.1029/2008JD010619, 2009a.
- 5 Waquet, F., Léon, J. -F., Cairns, B., Goloub, P., Deuzé, J. -L., and Auriol, F.: Analysis of the spectral and angular response of the vegetated surface polarization for the purpose of aerosol remote sensing over land, App. Opt., 48, 1228–1236, 2009b.
- Wiscombe, W. J.: Improved Mie scattering algorithms, App. Opt., 19, 1505–1509, 1981.

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Table 1. Dimensions of LUTs for aerosol retrieval.

Variable name	No. of entries	Entries
Wavelength	3	0.490 μm , 0.675 μm , 0.870 μm
Solar zenith angle (degree)	21	0, 4, 8, ..., 80
View zenith angle (degree)	21	0, 4, 8, ..., 80
Relative azimuth angle (degree)	37	0, 5, 10, ..., 180
AOD	11	0, 0.1, 0.2, 0.3, 0.5, 0.8, 1.0, 1.2, 1.5, 2.0, 3.6
FMF	11	0, 0.1, 0.2, ..., 1

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Table 2. Detailed parameters of fine model and coarse model.

Aerosol models	$Rm(\mu m)$	S	m (0.675 μm)	m (0.870 μm)
Fine 1	0.219	0.531	1.480–0.0086i	1.485–0.0088i
Fine 2	0.257	0.535	1.483–0.0074i	1.483–0.0078i
Fine 3	0.208	0.619	1.549–0.0024i	1.537–0.0023i
Fine 4	0.192	0.504	1.458–0.0100i	1.468–0.0102i
Fine 5	0.177	0.474	1.472–0.0088i	1.482–0.0090i
Fine 6	0.162	0.538	1.535–0.0037i	1.536–0.0036i
Coarse 1	2.724	0.583	1.480–0.0086i	1.485–0.0088i
Coarse 2	2.580	0.568	1.483–0.0074i	1.483–0.0078i
Coarse 3	2.915	0.618	1.458–0.0100i	1.468–0.0102i
Coarse 4	2.265	0.656	1.472–0.0088i	1.482–0.0090i
Coarse 5	2.286	0.594	1.535–0.0037i	1.536–0.0036i
Coarse 6	2.241	0.531	1.549–0.0024i	1.537–0.0023i

The size distribution parameters, median radius (Rm), and standard deviation (S), are based on a lognormal distribution. “ m ” is the refractive index at the 0.675, 0.870 μm wavelengths.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

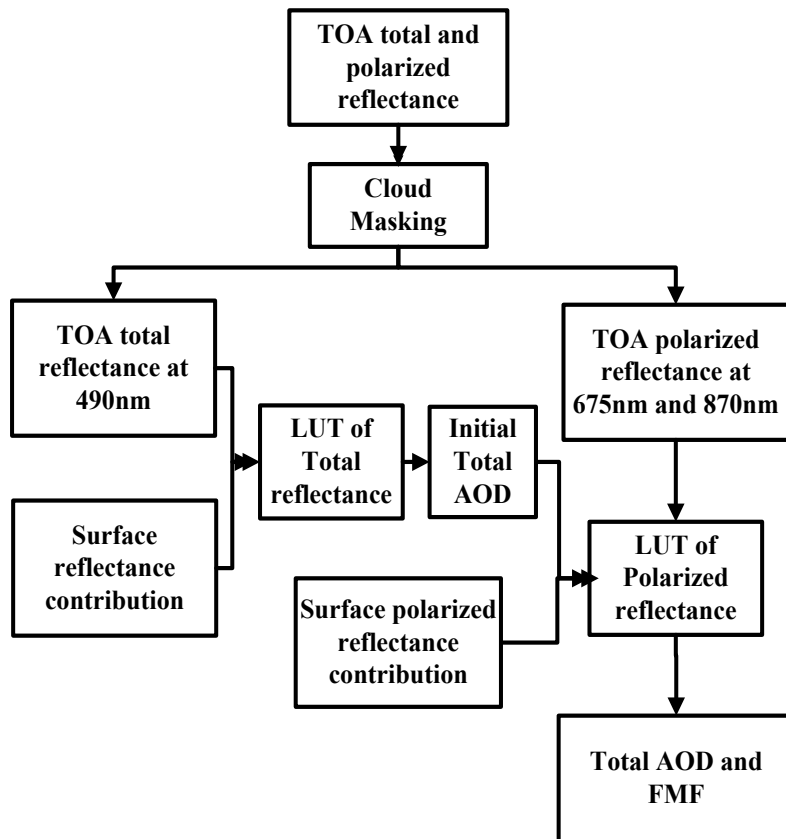



Fig. 1. Flowchart of aerosol optical properties from multi-angular, multi-spectral, total and polarized radiation measurements from POLDER.

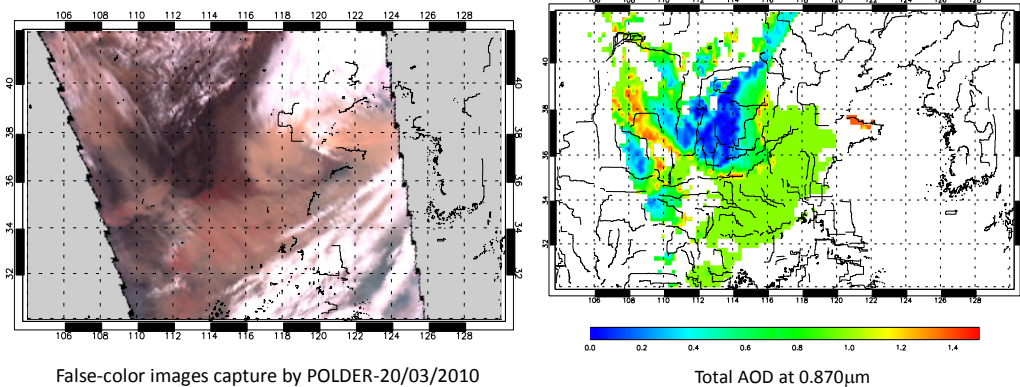


Fig. 2. Retrieved products from multi-angular, multi-spectral, total and polarized measurements on 20 March 2010.

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



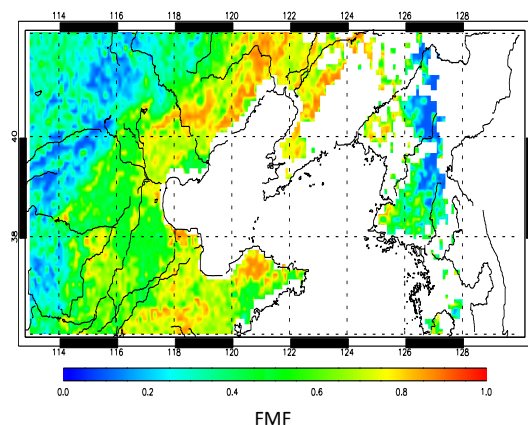
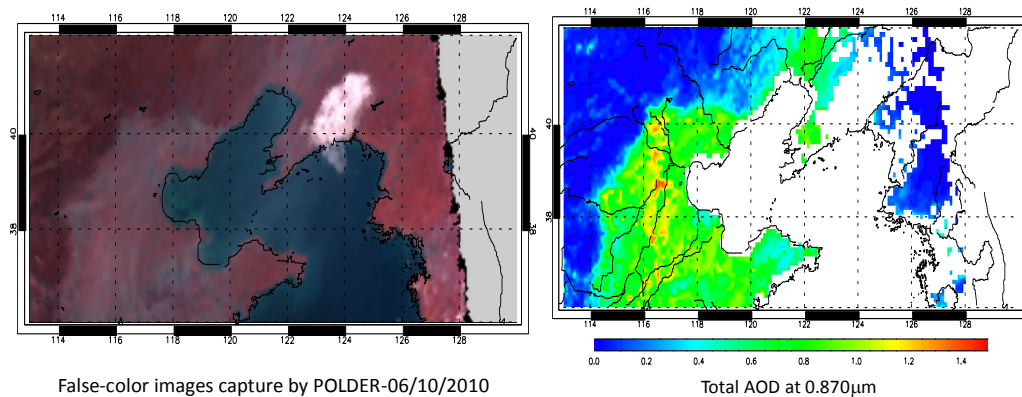


Fig. 3. Retrieved products from multi-angular, multi-spectral, total and polarized measurements on 6 October 2010.

AMTD

4, 5689–5716, 2011

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



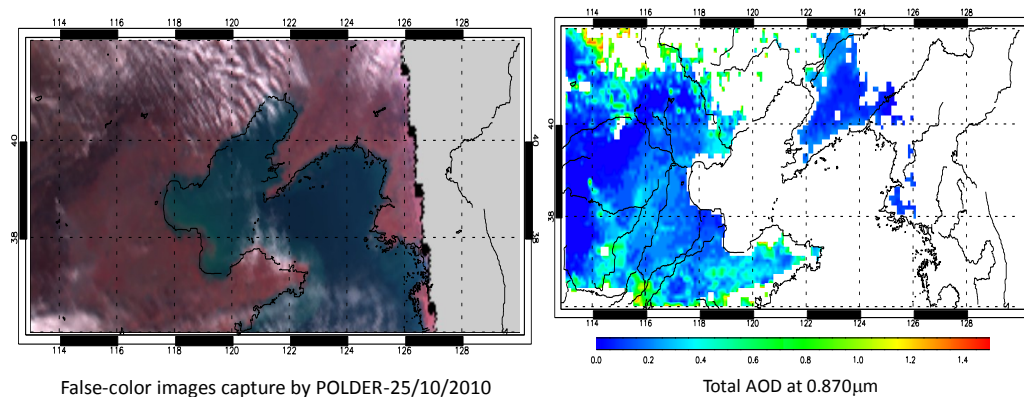


Fig. 4. Retrieved products from multi-angular, multi-spectral, total and polarized measurements on 25 October 2010.

Aerosol optical depth and fine-mode fraction retrieval

T. Cheng et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



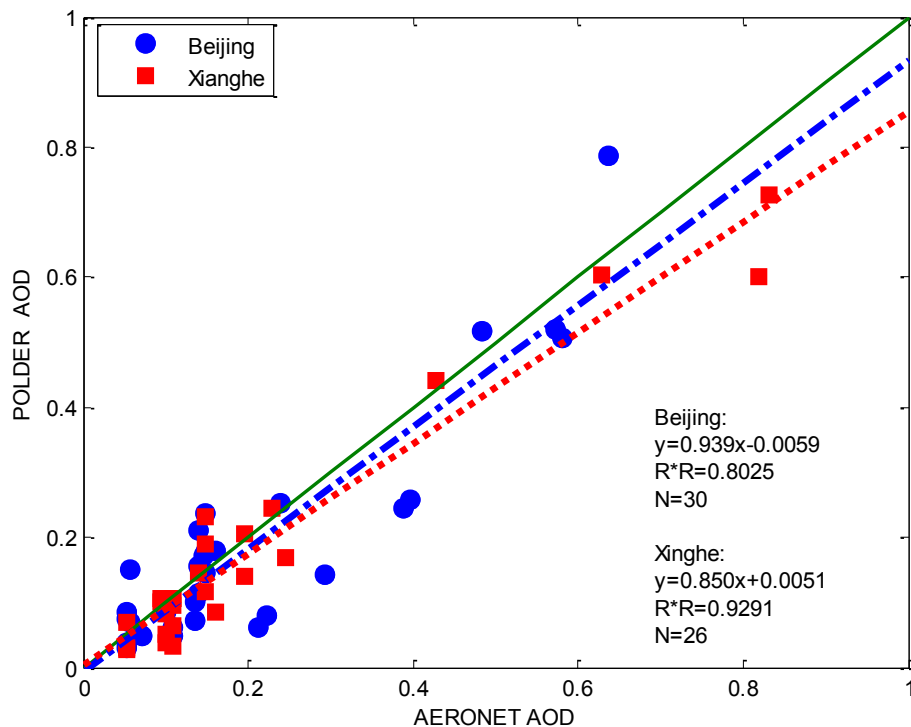


Fig. 5. Comparison of AOD retrieved present algorithm with those of AERONET observations at Beijing and Xianghe from September to December in 2010.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Aerosol optical depth
and fine-mode
fraction retrieval**

T. Cheng et al.

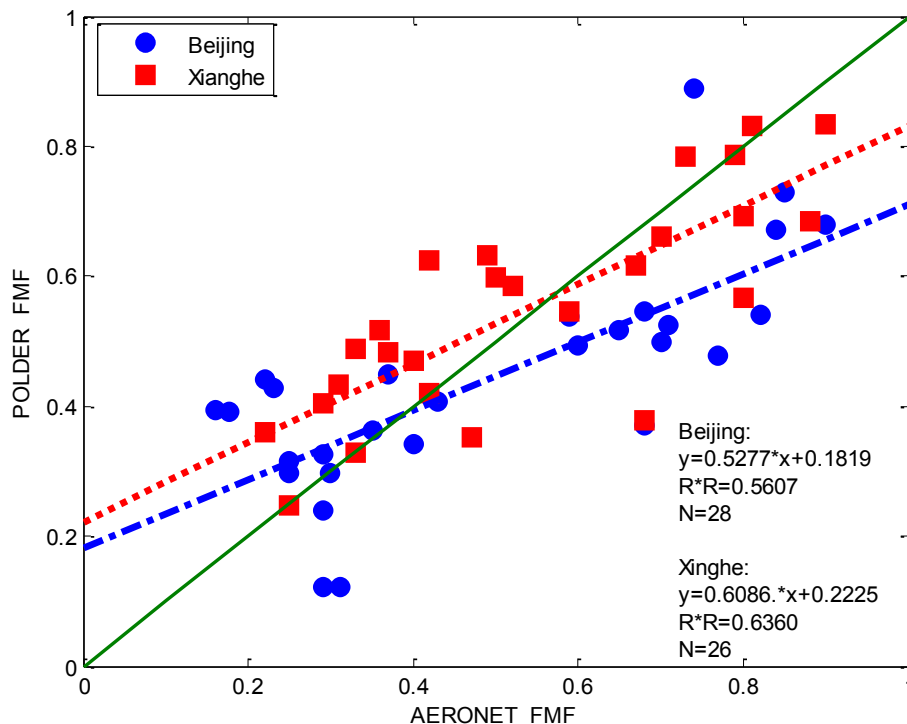


Fig. 6. Comparison of FMF retrieved present algorithm with those of AERONET observations at Beijing and Xianghe from September to December in 2010.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



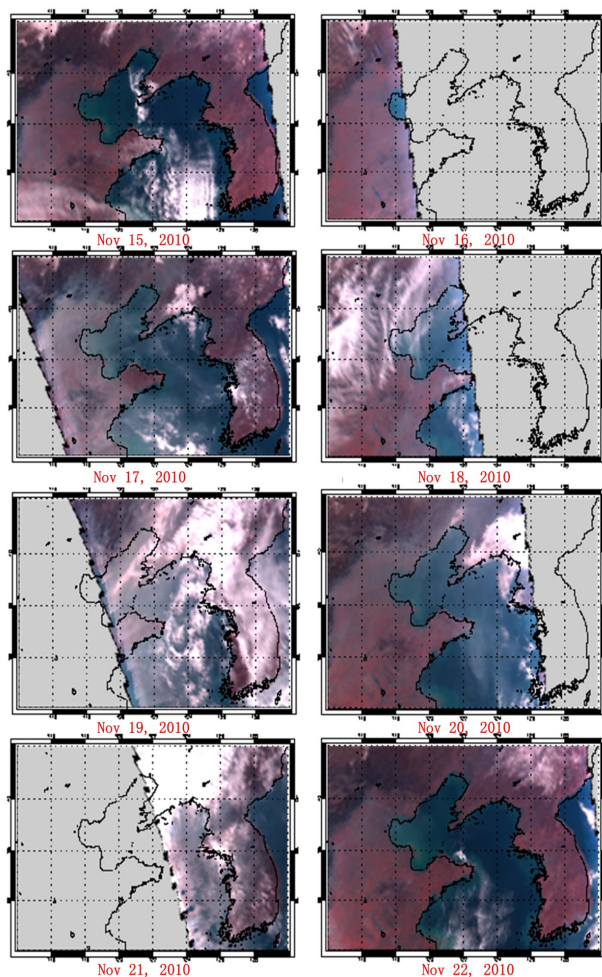


Fig. 7. False-color images over East Asia captured by POLDER during 15–22 December 2010.

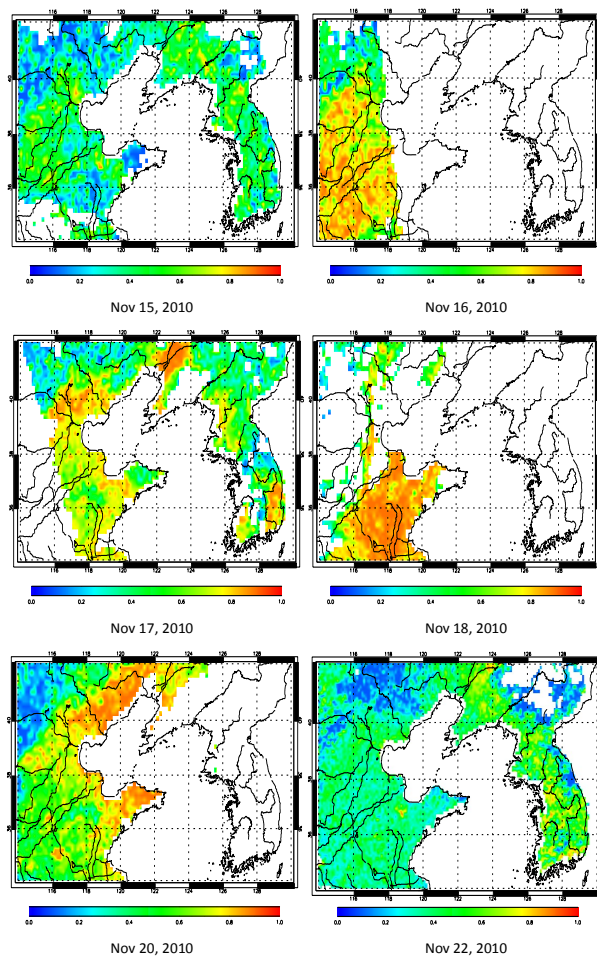


Fig. 8. Aerosol fine-mode (FMF) over the East Asia during 15–22 December 2010, except for 19 November, and 21 November due to cloud contaminated.

**Aerosol optical depth
and fine-mode
fraction retrieval**

T. Cheng et al.

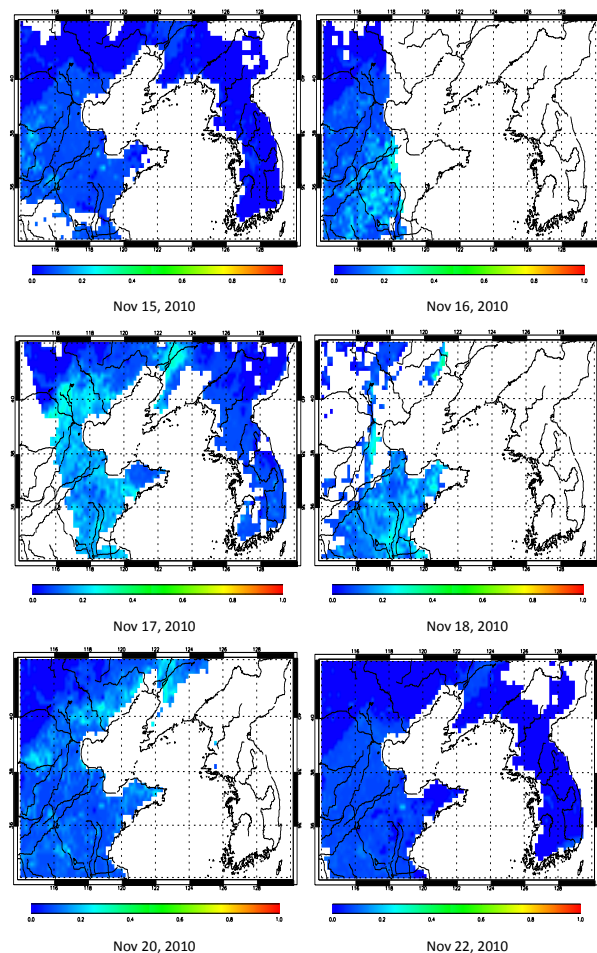


Fig. 9. Aerosol optical depth contributed by fine mode (Fine AOD) over East Asia during 15–22 December 2010, except for 19 November, and 21 November due to cloud contaminated.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

