VALIDATION OF A SIMPLIFIED AEROSOL RETRIEVAL ALGORITHM (SARA) OVER BEIJING

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ABSTRACT: Simplified Aerosol Retrieval Algorithm (SARA) retrieves aerosol optical depth (AOD) by incorporating a wide range of aerosol types (ω_o = 0.30–1.0) and independent of the common technique of constructing a look–up–table (LUT). In this study, the SARA AOD was retrieved at 500 m resolution using MODerate resolution Imaging Spectroradiometer (MODIS) data products (MOD02, MOD03, and MOD09) and local AErosol RObotic NETwork (AERONET) site "Beijing" over urban areas of Beijing for the year 2010. For the comparison purposes, the MODIS Dark–Target (DT) AOD observations at 10 km resolution were obtained from MODIS Collection 5.1 (C5.1) aerosol product for the same time period. The retrieved AOD observations from both algorithms (SARA and DT) were validated against Beijing_RADI AERONET AOD measurements and the data quality was evaluated using the Confidence Envelope of Expected Error (CEEE). The SARA algorithm achieved better data quality of 98.08% with higher correlation (R ~ 0.990) than the MODIS DT algorithm with very poor data quality of 31% with lower correlation (R ~ 0.946). Data quality was also evaluated for low (AOD < 0.40) to high (AOD > 0.40) aerosol loadings using CEEE and as a result the SARA algorithm achieved 67–69% better data quality than MODIS DT algorithm. The results demonstrate that the SARA algorithm is better than MODIS DT algorithm to retrieved AOD over Beijing under low to high aerosol loadings, including dust storms.

INTRODUCTION

Aerosol particles are responsible for poor air quality, impact on human health (Pope et al., 2002), and uncertainty in the climate system (Kaufman et al., 2002; Sun and Ariya, 2006). Aerosol RObotic NETwork (AERONET) (Holben et al., 1998, 2001) has been established for regular monitoring of aerosol optical properties, such as aerosol optical depth (AOD) only at point locations. Satellite remote sensing has been used to retrieve spatial distribution of AOD from local to global scales. AOD can be obtained from sensors such as the Advance Very High Resolution Radiometer (AVHRR) (Hauser et al., 2005; Riffler et al., 2010), the Sea-viewing Wide Field –of –view Sensor (SeaWiFS) (Sayer et al., 2012), the Multi–angle Imaging Spectroradiometer (MISR) (Kahn et al., 2005, 2010), the Total Ozone Mapping Spectrometer (TOMS) (Torres et al., 2002), the Ozone Monitoring Instrument (OMI) (Torres et al., 2007), the MEdium Resolution Imaging Spectroradiometer (MERIS) (Vidot et al., 2008), and the MODerate resolution Imaging Spectroradiometer (MODIS) (Levy et al., 2007b, 2010; Remer et al., 2005, 2008). MODIS aboard on Terra and Aqua satellites since 1999 and 2002, respectively, has a 36 channels ranging from 0.41 to 14 μm with spatial coverage from 250 m to 1 km, good temporal resolution of 1 to 2 days and swath width of 2330 km. The traditional MODIS Dark–Target (DT) algorithm retrieves AOD over land at 10 km spatial resolution (Kaufman et al., 1997b; Levy et al., 2007a, 2010, Remer et al., 2005, 2008). In the DT algorithm, the 500 m pixels within the retrieval window of 20 x 20 (400 pixels) are masked for clouds, snow/ice and other bright surfaces. Dark surfaces are selected for surface reflectance between 0.01 and 0.25 at 2.21 μm channel, and darkest 20% and brightest 50% are deselected at 0.66 μm channel. Surface reflectance is estimated as function of NDV_{SWIR} and scattering angle for the remaining pixels, and at least 12 pixels should be present to perform aerosol retrieval. The DT algorithm has been validated regionally and globally (Hyer et al., 2011, Levy et al., 2010, Mi et al., 2007, Papadimas et al., 2009), and 72% of retrievals (QA flag = 3) fall within the Confidence of Expected Error (CEEE) on global basis (Levy et al., 2010). At city level, it was observed that only 12% of DT retrievals fall within CEEE over the bright surfaces of the Hong Kong International Air port (Bilal et al., 2013).

Recently, a Simplified Aerosol Retrieval Algorithm (SARA) was developed and validated over the complex and hilly surfaces of the Hong Kong (Bilal et al., 2013), and 78 to 100% of retrievals fall within CEEE. The objective of this study is to (i) validate SARA retrieved AOD at 500 m resolution over the urban surfaces of Beijing, a city with sparse vegetation cover and frequent high aerosol loadings, (ii) compare SARA with the traditional MODIS Collection 5.1 DT AOD at 10 km resolution, and (iii) evaluate the data quality of SARA and DT algorithm for low and high aerosol loadings using CEEE.

DATASETS

In this study, aerosol information of the year 2010 was obtained from ground–based AERONET station for the development of the SARA algorithm at 500 m resolution (Table 1). The solar and sensor viewing geometry, radiance and surface reflectance were obtained from MODIS level 1 (MOD02HKM, MOD03) and level 2 swath products (MOD09). The MODIS C5.1 aerosol product (MOD04) at 10 km resolution was obtained for comparison purposes for the year 2010 (Table 1).

Table 1: Summary of datasets used in the current study

Instrument/Product	Parameter	Resolution		Purpose
		Original	Used	
AERONET	AOD	-	-	Input/validation
MOD02HKM	Radiance	500 m	500 m	Input
MOD03	View angles	1000 m	1000 m	Input
MOD09	Surface reflectance	500 m	500 m	Input
MOD04 C5.1	AOD	10 km	10 km	Comparison

DATA PROCESSING

In this study, level 2.0 AOD data of the year 2010 from the AERONET site "Beijing" was input into the SARA algorithm to retrieve AOD at 500 m resolution, and level 1.5 from the AERONET site "Beijing_RADI" was used for validation of the SARA retrieved AOD. For comparison purpose, MODIS DT AOD at 10 km resolution was obtained from the parameter "Optical_Depth_Land_And_Ocean". In order to increase the number of validation samples, the SARA/DT AOD observations were averaged using 3 x 3 spatial window centered on the Beijing_RADI site, and the AERONET AOD was averaged between 10 am to 12 noon. A total of 52 and 26 of the SARA retrieved AOD and DT AOD observations, respectively, coincided with Beijing_RADI AOD measurements (Figure 1). The DT algorithm almost has half AOD observations compared with SARA AOD observations, as most of the DT observations were missing due to limitation of the algorithm which deselects pixels at 2.21 μm and 0.66 μm channels. In order to evaluate the retrieving power and performance of SARA and the DT algorithms, AOD was divided into low (AOD < 4.0) and high (AOD > 4.0) AOD levels, and data quality was evaluated using a Confidence Envelope of Expected Error (CEEE) (Equation 1).

$$CEEE = \left(CEEE = AOD_{Sunphotometer} - \left|\pm\left(0.05 + 0.15AOD_{Sunphotometer}\right)\right| \leq AOD_{satellite} \leq AOD_{Sunphotometer} + \left|\pm\left(0.05 + 0.15AOD_{Sunphotometer}\right)\right|\right) \quad (1)$$

RESUTLS AND DISCUSSION

The SARA retrieved AOD and DT AOD were validated with Beijing_RADI AOD for the year 2010 (Figure 1). In Figure 1, solid lines represent the regressions lines, dotted and dashed lines are the CEEE and 1:1 lines, respectively. The SARA retrieved AOD (N = 52) was highly correlated (R = 0.990) with AEROENT AOD with small root mean square error (RMSE) of 0.084 and mean absolute error (MAE) of 0.053 as compared to DT AOD (N = 26) having a correlation coefficient (R) of 0.946, large RMSE of 0.286 and MAE of 0.219. The SARA retrieved AOD appear highly accurate as the majority of the observations lie close to or on the 1:1 line and has a data quality of 98.08% as 51 out 52 observations fall within CEEE. MODIS DT AOD is overestimated as most of the retrievals fall outside the upper limit of CEEE and only 31% of retrievals within CEEE. The MODIS DT algorithm exhibits poor data quality over Beijing, as was also observed in previously reported studies (Li et al., 2007; Xie et al., 2011). In general, the data quality of the MODIS DT algorithm is observed to be affected by aerosol model and the surface reflectance (Chu et al., 2002; Li et al., 2007; He et al., 2010; Xie et al., 2011). The results suggest that the SARA algorithm is superior to the MODIS DT algorithm over Beijing as it has better ability to retrieved AOD at higher resolution during low to high aerosol loadings, with higher correlation, low errors and very good data quality. The SARA algorithm also achieved high accuracy than previously reported studies of the DT algorithm (Li et al., 2007; Qi et at., 2013; Wang et al., 2007; Xie et al., 2011) and other developed aerosol algorithms over Beijing (Li et al., 2012; Wang et al., 2012).

The SARA retrieved AOD and DT AOD observations were categorised into low (AOD < 0.40) and high (AOD > 0.40) aerosol loadings (Li et al., 2003) to evaluate the performance of both the algorithms at Beijing_RADI AERONET site using CEEE (Table 2). Table 2 shows that SARA can retrieve AOD very well over Beijing as it has data quality from 90% to 100% and it has almost 3 to 6 times small RMSE and MAE errors than DT AOD for high to low aerosol loadings, respectively. On the other side, MODIS DT AOD has very poor data quality of 33% and 27% during low and high aerosol loadings, respectively. The results show that the SARA algorithm has almost 68% high data quality with small errors than the MODIS DT algorithm which suggests that the SARA algorithm is better able for retrieving AOD over urban surfaces of Beijing during low to high aerosol loadings.

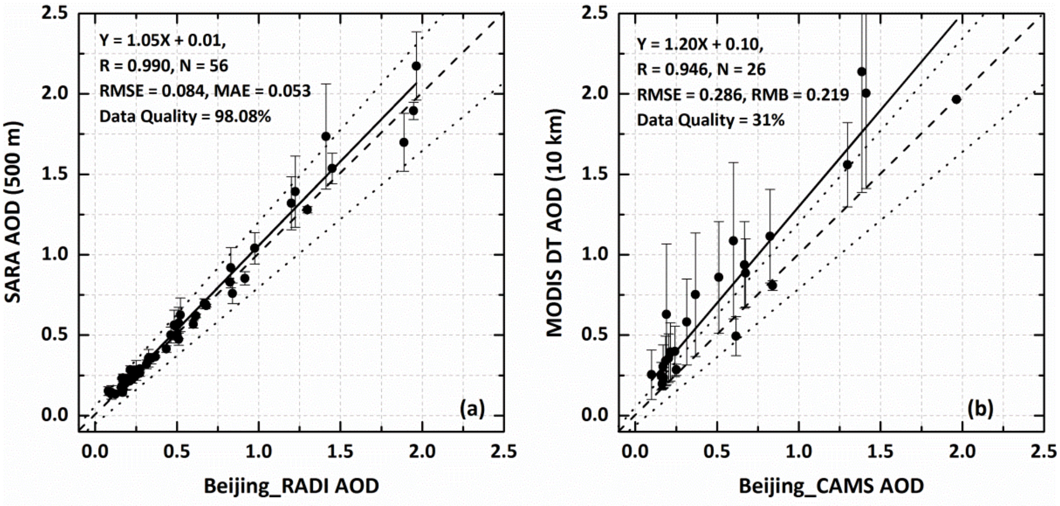

Figure 1: Validation of SARA AOD (500 m) and MODIS DT AOD (10 km) against Beijing_RADI AERONET AOD for the year 2010. The solid lines = regressions lines, dotted lines = CEEE lines and dashed lines = 1:1 lines.

Table 2: Data quality assessment using CEEE for low to high aerosol loadings for SARA and MODIS DT algorithms at Beijing_RADI

Low aerosol loadings (AOD < 0.40)				
Satellite Algorithm	N	RMSE	MAE	Data quality (%)
SARA	27	0.029	0.025	100
MODIS DT	15	0.198	0.155	33
High aerosol loadings (AOD > 4.0)				
SARA	25	0.117	0.086	96
MODIS DT	11	0.376	0.306	27

DUST STORM EVENT (15th March 2009)

Figure 2a is a MODIST Terra true color composite (RGB:143) of Beijing and Bohai Sea area under influence of dust storm (brown color) of 15th March 2009. Figure 2b shows that the MODIS DT algorithm was unable to retrieve AOD during this dust event and has many missing pixels due to its limitation of pixel thresholding in visible and SWIR channels. Figure 2c shows the spatial distribution of the dust AOD over Beijing and Bohai Sea regions retrieved by the SARA algorithm. The SARA algorithm was able to retrieve AOD over land as well as water surfaces with great accuracy. It was also observed that the SARA algorithm retrieved AOD in the same range as retrieved by MODIS DT algorithm over the region especially over the Bohai Sea area. For this, SARA AOD was resampled to 10 km (Figure 2d) spatial resolution and extracted the same spatial extent covered by MODIS DT AOD was extracted. Figure 2d shows that SARA and MODIS DT AOD observations have the same range of AOD and similar spatial pattern over the Bohai Sea. The results suggest the reliability of the SARA algorithm to retrieved AOD during high dust event over the region.

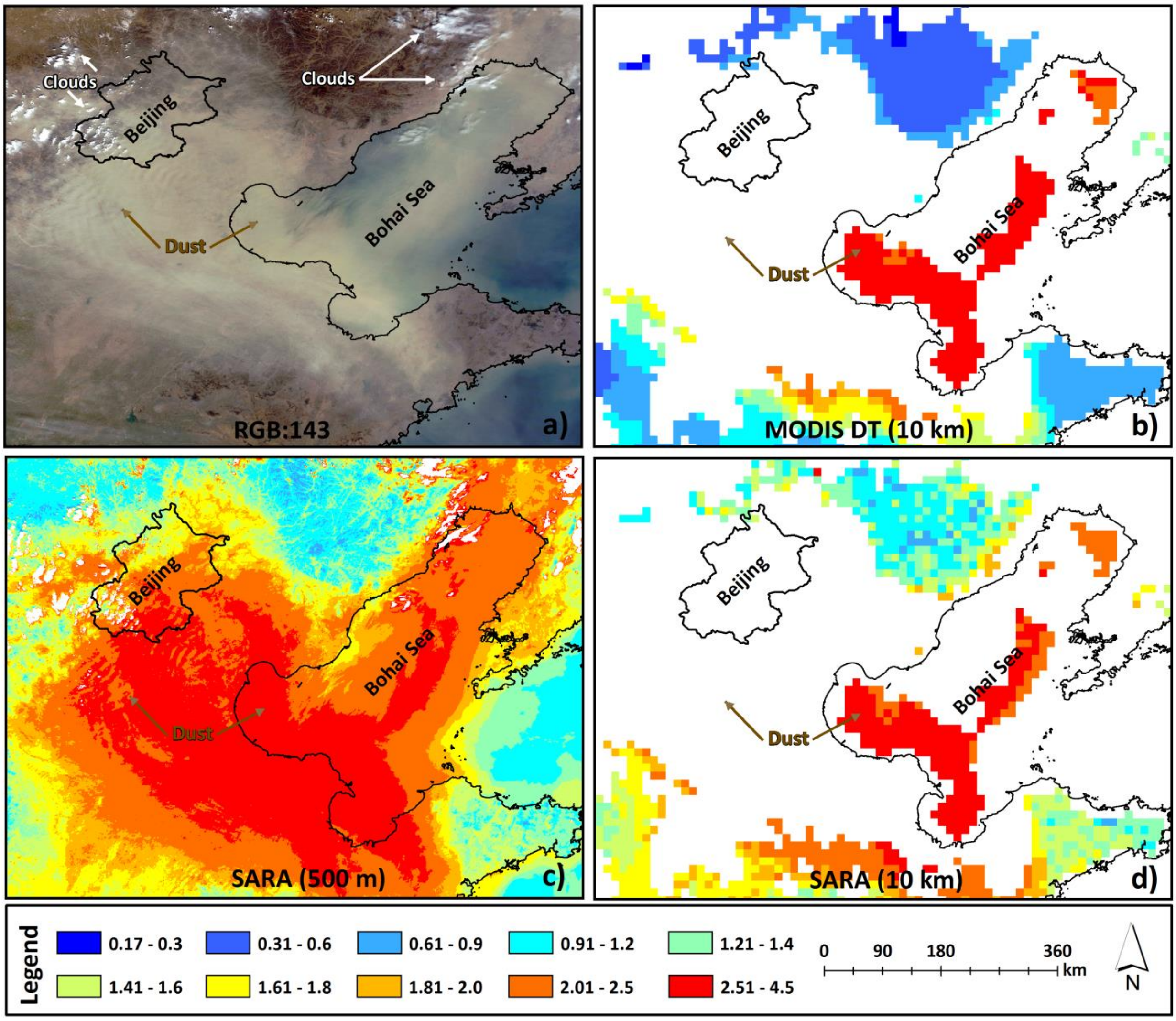

Figure 2: Dust Storm in Beijing and surrounding areas on 15th March 2009, where (a) MODIS Terra RGB:143 composite, (b) MODIS DT AOD at 10 km, (c) SARA retrieved AOD at 500 m, and (d) SARA AOD at 10 km.

CONCLUSION

The objective of this study was to evaluate the performance and data quality of the Simplified Aerosol Retrieval Algorithm (SARA) in Beijing during low to high aerosol loadings. The SARA retrieved AOD at 500 m resolution achieved higher correlation, small RMSE and MAE errors with Beijing_RADI AEROENT AOD measurements as compare to MODIS DT AOD observations. The results showed that the SARA algorithm has much better data quality than the MODIS DT algorithm for low (AOD < 0.40) to high (AOD > 4.0) AOD observations. During the dust storm in Beijing and Bohai Sea areas, the SARA algorithm was able to retrieved dust AOD and accurately represented the spatial distribution of dust over the regions, whereas the MODIS DT algorithm was unable to retrieve AOD and has a lot of missing pixels over the region due to its limitation of pixel selection. This study demonstrate that the SARA algorithm is superior to the MODIS DT algorithm and has much better ability to retrieve AOD over all types of surfaces including dark and bright land surfaces and over ocean during low to high aerosol loadings and dust storms.

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REFRENCES

Bilal, M., Nichol, J. E., Bleiweiss, M. P., & Dubois, D., 2013. A Simplified high resolution MODIS Aerosol Retrieval Algorithm (SARA) for use over mixed surfaces. Remote Sensing of Environment, 136, 135–145. doi:10.1016/j.rse.2013.04.014.

Chu, D.A., kaufman, Y.J., & Ichoku, C., 2002. Validation of MODIS aerosol optical depth retrieval over land. Geophysics Research Letters, 29 (12), 8007.

Hauser, A., Oesch, D., Foppa, N., & Wunderle, S., 2005. NOAA AVHRR derived aerosol optical depth over land. Journal of Geophysical Research, 110(D8), D08204. doi:10.1029/2004JD005439.

He, Q., Li, C., Tang, X., Li, H., Geng, F., & Wu, Y., 2010. Validation of MODIS derived aerosol optical depth over the Yangtze River Delta in China. Remote Sensing of Environment, 114, 1649–1661.

Holben, B. N., Eck, T. F., Slutsker, I., Tanré, D., Buis, J. P., Setzer, A., … Smirnov, A., 1998. AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization. Remote Sensing of Environment, 66(1), 1–16. doi:10.1016/S0034-4257(98)00031-5.

Holben, N., Tanr, D., Smirnov, A., Eck, T. F., Slutsker, I., Newcomb, W. W., … Zibordi, G., 2001. An emerging ground-based aerosol climatology : Aerosol optical depth from AERONET, 106(Dll).

Kahn, R. A., Gaitley, B. J., Garay, M. J., Diner, D. J., Eck, T. F., Smirnov, A., & Holben, B. N., 2010. Multiangle Imaging SpectroRadiometer global aerosol product assessment by comparison with the Aerosol Robotic Network. Journal of Geophysical Research, 115(D23), D23209. doi:10.1029/2010JD014601

Kahn, R. A., Gaitley, B. J., Martonchik, J. V., Diner, D. J., Crean, K. A., & Holben, B., 2005. Multiangle Imaging Spectroradiometer (MISR) global aerosol optical depth validation based on 2 years of coincident Aerosol Robotic Network (AERONET) observations. Journal of Geophysical Research, 110(D10), D10S04. doi:10.1029/2004JD004706

Kaufman, Y. J., Tanré, D., & Boucher, O., 2002. A satellite view of aerosols in the climate system. Nature, 419(6903), 215–23. doi:10.1038/nature01091.

Li, Z., Niu, F., Lee, K. -H., Xin, J., Hao, W. M., Nordgren, B., et al., 2007. Validation and understanding of Moderate Resolution Imaging Spectroradiometer aerosol products (C5) using ground-based measurements from the handheld Sun photometer network in China. Journal of Geophysical Research, 112 (22), 1–16.

Li, Y.J., Xue, Y., He., X.W., Jie, G., 2012. High-resolution remote sensing retrieval over urban areas by synergetic use of HJ-1 CCD and MODIS data. Atmospheric Environment, 46, 173–180.

Levy, R. C., Remer, L. a., Mattoo, S., Vermote, E. F., & Kaufman, Y. J., 2007. Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance. Journal of Geophysical Research, 112(D13), D13211.

Levy, R. C., Remer, L. a., Kleidman, R. G., Mattoo, S., Ichoku, C., Kahn, R., & Eck, T. F., 2010. Global evaluation of the Collection 5 MODIS dark-target aerosol products over land. Atmospheric Chemistry and Physics, 10(21), 10399–10420.

Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA : The Journal of the American Medical Association, 287(9), 1132–41.

Qi, Y.L., Ge, J.M., & Huang, J.P., 2013. Spatial and temporal distribution of MODIS and MISR aerosol optical depth over northern China and comparison with AERONET. Chinese Science Bulletin, 58, 2497–2506.

Remer, L. a., Kaufman, Y. J., Tanré, D., Mattoo, S., Chu, D. a., Martins, J. V., … Holben, B. N., 2005. The MODIS Aerosol Algorithm, Products, and Validation. Journal of the Atmospheric Sciences, 62(4), 947–973. doi:10.1175/JAS3385.1

Remer, L. a., Kleidman, R. G., Levy, R. C., Kaufman, Y. J., Tanré, D., Mattoo, S., … Holben, B. N., 2008. Global aerosol climatology from the MODIS satellite sensors. Journal of Geophysical Research, 113(D14), D14S07. doi:10.1029/2007JD009661

Sun, J., & Ariya, P., 2006. Atmospheric organic and bio-aerosols as cloud condensation nuclei (CCN): A review. Atmospheric Environment, 40, 795- 820.

Riffler, M., Popp, C., Hauser, A., Fontana, F., & Wunderle, S., 2010. Validation of a modified AVHRR aerosol optical depth retrieval algorithm over Central Europe. Atmospheric Measurement Techniques, 3(5), 1255–1270. doi:10.5194/amt-3-1255-2010.

Sayer, A. M., Hsu, N. C., Bettenhausen, C., Jeong, M.-J., Holben, B. N., & Zhang, J., 2012. Global and regional evaluation of over-land spectral aerosol optical depth retrievals from SeaWiFS. Atmospheric Measurement Techniques, 5(7), 1761–1778. doi:10.5194/amt-5-1761-2012.

Torres, O., Bhartia, P. K., Herman, J. R., Sinyuk, A., Ginoux, P., & Holben, B., 2002. A Long-Term Record of Aerosol Optical Depth from TOMS Observations and Comparison to AERONET Measurements. Journal of the Atmospheric Sciences, 59(3), 398–413.

Torres, O., Tanskanen, A., Veihelmann, B., Ahn, C., Braak, R., Bhartia, P. K., … Levelt, P., 2007. Aerosols and surface UV products from Ozone Monitoring Instrument observations: An overview. Journal of Geophysical Research, 112(D24), D24S47. doi:10.1029/2007JD008809.

Vidot, J., Santer, R., & Aznay, O., 2008. Evaluation of the MERIS aerosol product over land with AERONET. Atmospheric Chemistry and Physics, 8(24), 7603–7617. doi:10.5194/acp-8-7603-2008.

Wang, L. L., Xin, J.Y., Wang, Y.S., Li, Z.Q., Liu, G.R., & Li, J., 2007. Evaluation of the MODIS aerosol optical depth retrieval over different ecosystems in China during EAST–AIRE. Atmospheric Environment, 41 (33), 7138–7149.

Wang, Y., Xue, Y., Li, Y., Guang, J., Mei, L., Xu, H., et al., 2012. Prior knowledge-supported aerosol optical depth retrieval over land surfaces at 500 m spatial resolution with MODIS data. International Journal of Remote Sensing, 33, 674–691.

Xie, Y., Zhang, Y., Xiong, X., Qu, J. J., & Che, H., 2011. Validation of MODIS aerosol optical depth product over China using CARSNET measurements. Atmospheric Environment, 45(33), 5970–5978.