Retrieval, Inter-comparison, and Validation of Above-cloud Aerosol Optical Depth from A-train Sensors

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Abstract

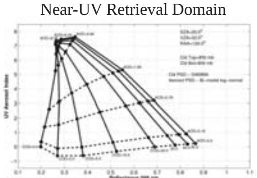
Absorbing aerosols produced from biomass burning and dust outbreaks are often found to overlay lower level cloud decks and pose greater potentials of exerting positive radiative effects (warming) whose magnitude directly depends on the aerosol loading above cloud, optical properties of clouds and aerosols, and cloud fraction. Recent development of a 'color ratio' (CR) algorithm applied to observations made by the Aura/OMI and Aqua/MODIS constitutes a major breakthrough and has provided unprecedented maps of above-cloud aerosol optical depth (ACAOD). The CR technique employs reflectance measurements at TOA in two channels (354 and 388 nm for OMI; 470 and 860 nm for MODIS) to retrieve ACAOD in near-UV and visible regions and aerosol-corrected cloud optical depth, simultaneously. An inter-satellite comparison of ACAOD retrieved from NASA's A-train sensors reveals a good level of agreement between the passive sensors over the homogeneous cloud fields.

Direct measurements of ACA such as carried out by the NASA Ames Airborne Tracking Sunphotometer (AATS) and Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (4STAR) can be of immense help in validating ACA retrievals. We validate the ACA optical depth retrieved using the CR method applied to the MODIS cloudy-sky reflectance against the airborne AATS and 4STAR measurements. A thorough search of the historic AATS-4STAR database collected during different field campaigns revealed five events where biomass burning, dust, and wildfire-emitted aerosols were found to overlay lower level cloud decks observed during SAFARI-2000, ACE-ASIA 2001, and SEAC4RS-2013, respectively. The co-located satellite-airborne measurements revealed a good agreement (RMSE less than 0.1 for AOD at 500 nm) with most matchups falling within the estimated uncertainties in the MODIS retrievals. An extensive validation of satellite-based ACA retrievals requires equivalent field measurements particularly over the regions where ACA are often observed from satellites, i.e., south-eastern Atlantic Ocean, tropical Atlantic Ocean, northern Arabian Sea, South-East and North-East Asia.

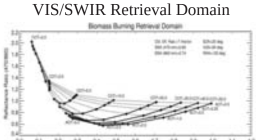
The Color Ratio Algorithm

- The presence of absorbing aerosols above cloud decks reduces the amount of upwelling ultraviolet (UV), visible (VIS), and shortwave infrared radiation reaching the top of atmosphere and produces a strong color ratio effect in the spectral reflectance measurements. This is often referred to as "cloud darkening"—an effect caused by the spectral aerosol absorption .
- The CR technique employs reflectance measurements at TOA in two channels (354 and 388 nm for OMI; 470 and 860 nm for MODIS) to retrieve above-cloud AOD in near-UV and visible regions and aerosol-corrected cloud optical depth, simultaneously.

Near-UV Retrieval Domain



VIS/SWIR Retrieval Domain



Input Parameters
TOA reflectance
OMI: 354 and 388 nm
MODIS: 470 and 660/860 nm (ocean/land)

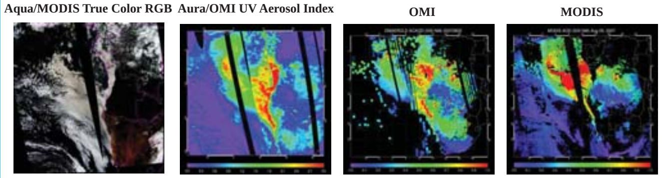
A priori:
Aerosol Model (size distribution, real/imaginary part of refractive indices, aerosol vertical profile, cloud droplet distribution (modified-Gamma), Cloud top/bottom pressure

RT Model: VLIDORT V2.6

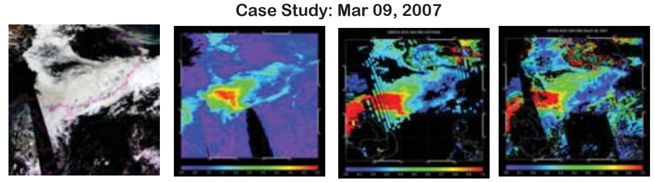
Output Parameters
Above-cloud AOD
(at 388 for OMI and at 660/860 nm for MODIS)
aerosol-corrected COD

Case Study: Aug 05, 2007

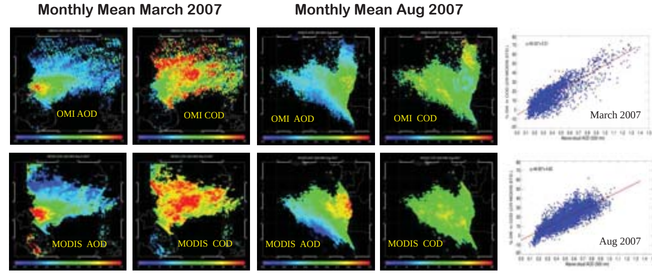
Aqua/MODIS True Color RGB | Aura/OMI UV Aerosol Index | Cloud-free + Above-cloud AOD Distribution: OMI | MODIS



Case Study: Mar 09, 2007



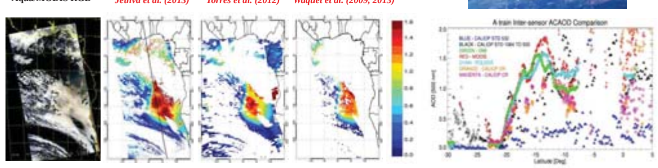
Monthly Mean March 2007 | Monthly Mean Aug 2007



A-train Multi-sensor Comparison of Above-cloud AOD

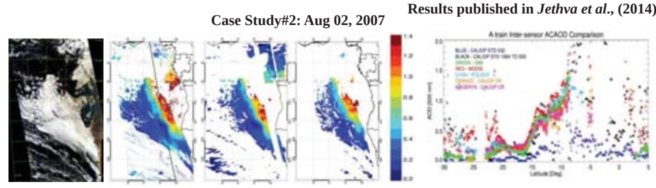
Case Stude#1: Aug 13, 2006

Aqua/MODIS RGB | Aqua/MODIS ACAOD *Jethva et al. (2013)* | Aura/OMI ACAOD *Torres et al. (2012)* | POLDER ACAOD *Waquet et al. (2009, 2013)*



Results published in *Jethva et al.*, (2014)

Case Study#2: Aug 02, 2007



Validation of Above-cloud AOD

AATS-14

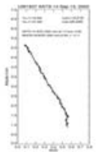
4STAR

The ***Ames Airborne Tracking Sunphotometer (AATS)*** and ***Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research (4STAR)*** developed by the NASA AMES research group measures the transmission of the solar beam in 14 spectral bands (0.3535, 0.3800, 0.4490, **0.4994**, 0.5246, 0.6057, 0.6751, 0.7784, 0.8645, 1.0191, 1.2413, 1.5574 μm) and subsequently retrieve the columnar aerosol optical depths (AOD). AATS's azimuth and elevation motors controlled by differential sun sensors rotate a tracking head, which locks the detector normal to the solar beam thus provides the direct measurements of solar transmission. Further information on AATS can be found in *Russell et al.*, 2002; *Schmid et al.*, 2003 as well as at web link: http://geo.arc.nasa.gov/sgg/AATS-website/AATS6_AATS14/AATS6_AATS14.html.

AATS/4STAR
Field campaign participation:
TARFOX (1996)
ACE-2
SAFARI-2000
ACE-Asia (2001)
CLAMS,
SEAC4RS-2013 (4STAR)

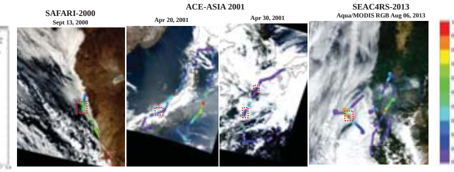
- Aerosol models needed for the MODIS ACAOD retrievals were developed on the basis of long-term measurements made by AERONET in the respective regions.
- MODIS above-cloud AOD was co-located within 10-20 km radius of the airborne measurements

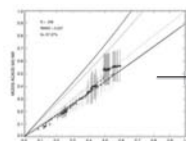
MODIS AOD is scaled to the altitude of airborne measurements



Terra/MODIS True Color RGB & AATS Path

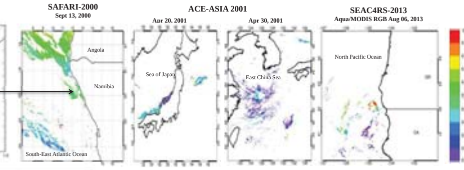
SAFARI-2000 Sept 13, 2000 | ACE-ASIA 2001 Apr 20, 2001 | Apr 30, 2001 | SEAC4RS-2013 Aqua/MODIS RGB Aug 06, 2013

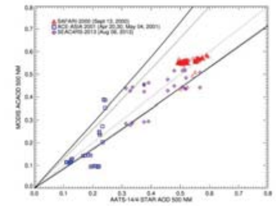




MODIS Above-cloud AOD Retrieval

SAFARI-2000 Sept 13, 2000 | ACE-ASIA 2001 Apr 20, 2001 | Apr 30, 2001 | SEAC4RS-2013 Aqua/MODIS RGB Aug 06, 2013





Field Campaign	AAC Event	N	RMSE	Q (%)
SAFARI-2000	Sept 13, 2000	104	0.038	98.08
ACE-ASIA 2001	Apr 20, 30, May 04	3, 20, 4	0.139, 0.064, 0.027	0.00, 55, 100
SEAC4RS-2013	Aug 06, 2013 (Terra, Aqua)	12, 12	0.071, 0.070	33.33, 100

Notations: N: number of MODIS-AATS matchups; RMSE: root-mean-square-error; Q: % of matchups within the estimated uncertainty of -10% to +50%

- Most satellite-airborne matchups falling within the predicted uncertainties in the above-cloud AOD retrieval (-10% to 50%)
- The co-retrieved COD was found to be either equivalent to the MODIS operational cloud product for lower AODs (ACE-ASIA) or higher by 30-35% for more absorbing aerosol event of SAFARI-2000

References

Torres, O., H. Jethva, and P. K. Bhartia, "Retrieval of aerosol optical depth above clouds from OMI observations: Sensitivity analysis and case studies," *J. Atmos. Sci., vol. 69, no. 3, pp. 1037–1053, doi:* http://dx.doi.org/10.1175/JAS-D-11-0130.1

Jethva, H., O. Torres, L. A. Remer, and P. K. Bhartia, "A Color Ratio Method for Simultaneous Retrieval of Aerosol and Cloud Optical Thickness of Above-Cloud Absorbing Aerosols From Passive Sensors: Application to MODIS Measurements, *IEEE Trans. Geosci. Rem. Sens., issue 99, pp. 1-9, doi: 10.1109/TGRS.2012.2230008*

Jethva, H., O. Torres, F. Waquet, D. Chand, and Y. Hu (2014), How do A-train sensors intercompare in the retrieval of above-cloud aerosol optical depth? A case study-based assessment, Geophys. Res. Lett., 41, 186–192, doi:10.1002/2013GL058405.

Chand, D., T. L. Anderson, R. Wood, R. J. Charlson, Y. Hu, Z. Liu, and M. Vaughan, "Quantifying above-cloud aerosol using spaceborne lidar for improved understanding of cloudy-sky direct climate forcing," *J. Geophys. Res., vol. 113, no. D13, pp. D13206-1 D13206-12*

Waquet, F., J. Riedi, L. C. Labonnote, P. Goloub, B. Cairns, J.-L. Deuzeand, and D. Tanre, "Aerosol remote sensing over clouds using a-train observations," *J. Atmos. Sci., vol. 66, no. 8, pp. 2468–2480.*

Russell, P. B., Flatau, P. J., Valero, F. P. J., Nakajima, T., Holben, B., Pilewskie, P., Bergin, M., Schmid, B., Bergstrom, R. W., Vogelmann, A., Bush, B., Redemann, J., Pope, S., Livingston, J., Leitner, S., Hsu, N. C., Wang, J., Seinfeld, J., Hegg, D., Quinn, P., and Covert, D., Overview of ACE-Asia Spring 2001 investigations on aerosol-radiation interactions, 11th Conference on Atmospheric Radiation, American Meteorological Society, Ogden, Utah, 3-7 June 2002, Postprint Volume, pp. 1-4.