Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth over Ocean (Collection 5) Technical Document

1. Intent of This Document

This document is intended for users who wish to compare satellite-derived observations with climate model output in the context of the CMIP5/IPCC experiments. It summarizes essential information needed for comparing this dataset to climate model output. References and useful links are provided.

This dataset is provided as part of an effort to increase the usability of NASA satellite observational data for the modeling and model analysis communities. This is not a standard NASA satellite instrument product, but does represent an effort on behalf of data experts to identify a product that is appropriate for routine model evaluation. This data have been reprocessed, reformatted, and created solely for comparisons with climate model output. Community feedback to improve and validate the dataset for modeling usage is appreciated. Email comments to HQ-CLIMATE-OBS@mail.nasa.gov .

Dataset Filename:

od550aer_MODIS_L3_C5_200003-201302.nc

Ancillary Filenames:

od550aerNobs_MODIS_L3_C5_200003-201302.nc,
od550aerStdv_MODIS_L3_C5_200003-201302.nc

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2. Data Origin and Field Description

MODIS (Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra and Aqua satellites (launched in December 1999 and May 2002, respectively). Both satellites are in a sun-synchronous orbit. Terra's orbit is timed so that daytime descending passes (from north to south) cross the equator in the morning (10:30 LT), while Aqua ascending passes (south to north) occur over the equator in the afternoon (13:30 LT). These orbits, with a 16-day repeat cycle on the World Reference System (WRS-2) grid, are precisely controlled and have remained extremely stable in both space and time. With a 2,330 km swath, each MODIS instrument views the entire Earth's surface every 1 to 2 days, acquiring data in 36 spectral channels (or "bands" in MODIS nomenclature), ranging from 0.41 μm to 14.5 μm. The spatial resolution varies between bands, with two bands at 250 m (at nadir views), five bands at 500 m, and the remainder at 1 km. Orbital data are cut into 5 minute sections, known as "granules", and only daytime orbits (approximately 140 granules per day) are used for aerosol retrieval. Orbital data are calibrated and geo-located, with the resulting dataset being archived and known as Level-1B data. See Section 6 for an overview of the MODIS instrument.

The MODIS aerosol product (archived Hierarchical Data Format (HDF) file, with filename MOD04_L2 and MYD04_L2 for MODIS Terra and Aqua, respectively) is known as a Level 2 product. It is derived by organizing the Level 1B data, and is produced at a nominal (for nadir view) native spatial resolution of 10 km. While aerosol retrieval algorithms are identical for both MODIS instruments, separate algorithms are used for retrieving aerosol properties over dark land, bright land and over oceans. Regardless of retrieval algorithm, the primary MODIS-derived Level 2 product is the aerosol optical depth (AOD) at 0.55 μm (550 nm). The CMIP5 product, described here, refers to an aggregation of MODIS-Terra, Level-2 (MOD04_L2) AOD product over the ocean only, from the specific Science Data Set (SDS) of name *Effective_Optical_Depth_Best_Ocean.* Note that there is a separate MODIS-team aggregation of AOD that results in a global 1° gridded (Level-3) dataset with daily (e.g. MOD08_D3), eight-day (MOD08_E3), and monthly temporal (MOD08_M3) resolution. All MODIS team products (e.g. MOD04_L2 and MOD08_M3) are available through the Level-1 and Atmosphere Archive and Data Distribution System (LAADS) at NASA Goddard Space Flight Center.

This CMIP5 monthly AOD dataset is over ocean, and from Terra only. It covers the time period from March 2000 through the most recently available processed month (December 2012 at the time of this writing). The CMIP5 product contains temporal and geometric coordinate variables (time, latitude, and longitude) along with the mean AOD. The time corresponds to the 16th day of the month and is given as the number of days since March 1, 2000. The latitude and longitude grid is equal-angle at 1° resolution. The longitude grid center range is from 0.5 to 359.5 degrees while the latitude extends from -89.5 to +89.5 degrees (south to north). The value of AOD is non-dimensional and ranges from zero to five.

CF variable name, units	**Long_Name:** Ambient Aerosol Optical Thickness at 0.55 μm **Standard Name:** atmosphere_optical_thickness_due_to_ambient_aerosol **Units:** dimensionless
Spatial resolution	1° equal angle
Temporal resolution	Monthly average, from March 2000–December 2012
Coverage	Global

The dataset includes two ancillary files. File named *od550aerStdv_MODIS_L3_C5_200003-201302.nc* provides the standard deviation of the individual observations that compris the month, for each equal-angle 1° grid-box. File named *od550aerNobs_MODIS_L3_C5_200003-201302.nc* gives the total monthly counts for all pixels included in each 1° grid-box. In the next section, we describe the MODIS Level-2 AOD retrieval algorithm, and how we process the MOD04_L2 dataset for the CMIP5 product.

3. Data Product Algorithm Overview

MODIS measures radiances in 36 spectral bands from the visible to the infrared with spatial resolution from 250 m to 1 km. Nineteen of these bands are known as reflected solar bands (RSBs) and range from approximately 0.41 μm to 2.11 μm, which covers the spectrum from “deep blue” through visible, near-infrared (NIR) and shortwave infrared (SWIR). All of these RSBs contain information about radiation that is reflected by Earth’s surface (land and ocean), clouds and aerosols. Like cloud detection, aerosol detection and retrieval is based on observing contrast (i.e. aerosol vs. background surface) for a given "target" area. However, aerosol properties can only be retrieved in clear-sky (non-cloudy) conditions. Unlike clouds, aerosol reflection has *spectral dependence*, meaning that their reflectance signal decreases as wavelength increases. For smaller "fine-mode" particles (e.g. having radius $r << 1\mu m$), where size is smaller than wavelength, the spectral dependence is steep, whereas for larger "coarse-mode" particles, there is little dependence on wavelength. The trick of an aerosol retrieval algorithm, then, is to A) select scenes (or pixels) which are not cloudy, B) use wavelength bands where the scattering properties of the Earth's surface are negligible or can be estimated with minimal uncertainty, and C) provide sufficient constraints on expected aerosol optical properties. Then the reflectance signal of the aerosol in the scene can be separated from the total observed signal, and the physical properties of the aerosol can be inferred. . Because of the different optical properties of land surfaces and ocean surfaces, separate retrieval algorithms are used for each surface type. Here we focus on the retrieval over oceans, for which the ocean surface is sufficiently dark to detect contrast by aerosols.

Retrieval of aerosol properties over ocean uses observations in six primary RSB bands. Additional MODIS bands, plus ancillary data, are used to filter out cloudy pixels, make corrections for gaseous absorption (water vapor, ozone and carbon dioxide), and otherwise limit contamination to a clear-sky aerosol retrieval. Details of the MODIS over-ocean aerosol retrieval algorithm, products, and modifications have been extensively reported in the literature (e,g, Tanré et al., 1996, Tanré et al., 1997, Remer et al., 2002; Remer et al., 2005; Remer et al., 2008). MODIS products are grouped together in "Collections", which are produced with consistent algorithms, with consistent instrument calibrations, and under consistent computer processing environments. The most recent completed Collection is known as Collection 5 (C005), which has been used to process the CMIP5 dataset.

The most complete description of the MODIS retrieval algorithm and Level 2 (MOD04_L2) product is provided in the online Algorithm Theoretical Basis Document (ATBD; Levy et al., 2009; http://modis-atmos.gsfc.nasa.gov/MOD04_L2/atbd.html). The algorithm is based on a "look-up table" (LUT) approach, i.e., radiative transfer calculations are pre-computed for a set of aerosol and surface parameters and compared with the observed radiation field. The algorithm assumes that one fine and one coarse lognormal aerosol modes can be combined with proper weightings to represent the ambient aerosol properties over the target. Spectral reflectance from the LUT is compared with MODIS-measured spectral reflectance to find the "best" (least-squares) fit. This is the solution to the retrieval. Also, the retrieval reports a more robust "average" for all solutions that meet certain fitting criteria. The following paragraphs provide some of the relevant details, however, the user is suggested to peruse the ATBD.

The retrieval uses pre-computed LUTs that are simulations of top-of-atmosphere (TOA) reflectance in the six MODIS bands. The TOA reflectance includes contributions from the ocean surface, from atmospheric molecules (Rayleigh), and from aerosols. The ocean surface includes contributions from (under-)water leaving radiance, from foam and whitecaps, and specular glitter, using a globally fixed wind speed of 6 m/s. Aerosol reflectance is computed from Mie theory, assuming spherical particles having spectrally varying, complex refractive indices. There are nine aerosol "modes", having size distributions that are lognormal with given median radius and standard deviation. Four of these modes are "fine" (with effective radii, $r_e < 0.25\ \mu m$), and five are "coarse" ($r_e > 1$

μm). Vector radiative transfer code is used to couple the surface with the atmosphere (aerosol + Rayleigh) for each of the nine aerosol modes, with TOA reflectance, atmospheric transmittance, and other properties computed at a variety of aerosol loadings and solar/sensor viewing geometries (e.g. solar zenith angles, sensor zenith angles and relative azimuth angles). Aerosol loadings are characterized by discrete values of AOD at 0.55 μm (e.g. = 0.0, 0.2, 0.5, 1.0, 2.0, 5.0), as index values for sorting the LUT. During the process of aerosol retrieval, the LUTs are stored into computer memory.

Prior to aerosol retrieval, the "Wisconsin" cloud mask file (known as MOD35_L2) has been produced from the geo-located, calibrated reflectance files. This file includes information about clouds (used for many downstream MODIS products), but also information about surface type and solar illumination including land, water, snow/ice, desert, and coast for both day and night. To produce a product at nominal 10 km resolution, the aerosol retrieval algorithm relies on inputs of calibrated, observed TOA spectral reflectance at native resolution (i.e. 500 m), for which errors are assumed to be negligible. It also uses some of the information included with the already produced cloud-mask file. Not all 500 m pixels are suitable for over-ocean aerosol retrieval. There is a complicated process (described in the ATBD; Levy et al., 2009), where non-retrievable pixels are discarded (known as "masking"). There is essentially a cascade of "if statement loops", that test for different problems. Over ocean, these include tests for excluding land pixels (e.g. coastlines, islands), tests for detecting under-water sediments, and a "glint mask" for excluding pixels close to the specular direction. At the same time, there are also a series of tests for masking cloudy pixels. The cloud masking includes some tests reported in the "upstream" MOD35_L2 cloud mask product, but also a number of tests performed specifically for the aerosol retrieval. There is a reflectance continuum between aerosols and clouds, so there is no perfect cloud mask. However, thresholds have been set to limit the amount of residual cloud contamination, yet maximize aerosol retrieval coverage. The aerosol retrieval can still be performed even in conditions of very high (e.g. nearly 90%) cloud fraction.

After all masking is performed, the 500 m resolution data are organized into 20 x 20 boxes (thus becoming 10 km x 10 km at nadir). The remaining non-masked pixels are sorted by their red-band reflectance (0.65 μm), and then the brightest 25% and darkest 25% are also discarded. Theoretically, these remaining pixels are far from clouds, cloud shadows and other problems, so that these are sufficiently characteristic of the clear-sky, dark-ocean surface within the 10 km aerosol pixel. These pixels are averaged to yield one set of spectral reflectance values, which becomes the observed spectral reflectance.

The actual retrieval is an inversion process, where the MODIS-observed spectral reflectance is iteratively compared with the simulated LUT. First the LUT is interpolated to the exact solar/sensor geometry of the MODIS observation. There are twenty possible combinations of fine and coarse modes (4 fine x 5 coarse) that can be weighted and normalized to approximate the spectral dependence and magnitude of the observed spectral reflectance. Each combination results in a total AOD (at 0.55 μm), a fine mode fraction (FMF), and a residual fitting error (ERR) in comparison to the observations. Out of the twenty combinations, one is the "best" solution. There is also an "average" solution, which is a more robust representation of all combinations meeting a fitting error threshold.

From the directly retrieved products (AOD, FMF, ERR and Fine/Coarse indices), one can derive a number of other products. These include such information as spectral AOD (and Ångstrom Exponent), aerosol effective radius, and other properties associated with the given aerosol solutions. At the same time, there are a number of diagnostic products that are calculated and reported as SDSs within the MOD04_L2 file. For example, there is information about the number of (500 m) pixels that was used (after masking and pixel sorting selection), as well as an assessment of the "aerosol" cloud fraction (non-retrievable fraction) associated with the retrieval. Finally, there is an estimate of "quality confidence" or QC for each retrieved aerosol pixel.

The report of QC is based on many tests, known as the "quality assurance plan". Some were performed during the cascade of statements used for masking. One notes how many pixels were used for retrieval, but also the presence of conditions that "almost" required masking. At the end of final retrieval, based on which tests may have failed or nearly failed, there is an estimate of confidence in the final product. These receive values that range from "3" (high confidence) to "0" (very low confidence). In essence, the QC characterizes how "happy" the algorithm was in producing a result. The monthly mean AOD over ocean described in this Technical Note is constructed from Level 2 retrievals having quality marks ranging from 1 to 3.

4. Validation and Uncertainty Estimates

MODIS aerosol results have been validated against a variety of observations, but has been most common to compare against ground-based sunphotometer data from the Aerosol Robotic Network (AERONET, Holben *et al.* 1998). In particular, Remer *et al.* (2008) report the performance of MODIS Collection 5 aerosol optical depth retrievals compared to AERONET in-situ measurements. MODIS aerosol optical depth (AOD) retrieved over oceans is strongly correlated with AERONET measurements with a 90% correlation coefficient. The expected error for ocean retrievals is $\pm(0.03+0.05 \times \text{AOD})$. AOD retrieved at the 550 nm channel falls within the expected error 60% of time. For additional information consult Remer *et al.* (2008).

5. Consideration for Model-Observation Comparisons

Satellite observations are the only means by which the global aerosol field can be completely and systematically observed. At present aerosol climatologies from current and heritage satellite data records differ in magnitude and monthly variability. These differences are due to a number of reasons: types of orbit, spatial resolution, diurnal sampling, spectral resolution and placement, satellite view geometry, cloud contamination, proper knowledge of surface characteristics, etc. In contrast to the spectrally-and/or spatially-challenged heritage data records, MODIS contains 36 spectral bands with at least a 1km spatial resolution at nadir. This combination of spectral and spatial resolutions allow for better detection of cloud and surface characteristics with fewer algorithmic assumptions.

The monthly dataset described in this Technical Note set is derived from Collection 5 MODIS Level-2 files with an additional screening designed to reduce the effects of cloud contamination (e.g., Zhang and Reid, 2006); no other correction has been applied to the data. MODIS aerosol optical depth retrievals are also available over land by two complementary algorithms: 1) the *Dark Target* algorithm (*e.g.,* Levy *et al.* 2007) and the *Deep Blue* algorithm (Hsu *et al.* 2004). As of this writing, the Collection 5 version of these algorithms does not yet include a combined land product. For this reason, aerosol optical depth retrievals from the MISR instrument (obs4MIPS dataset *od550aer_MISR_L3_F12_0022_200003-201211*) are currently recommended over land. As a combined land product becomes available with MODIS Collection 6, a similar MODIS-based monthly mean aerosol optical depth product over land will be added to obs4MIPS.

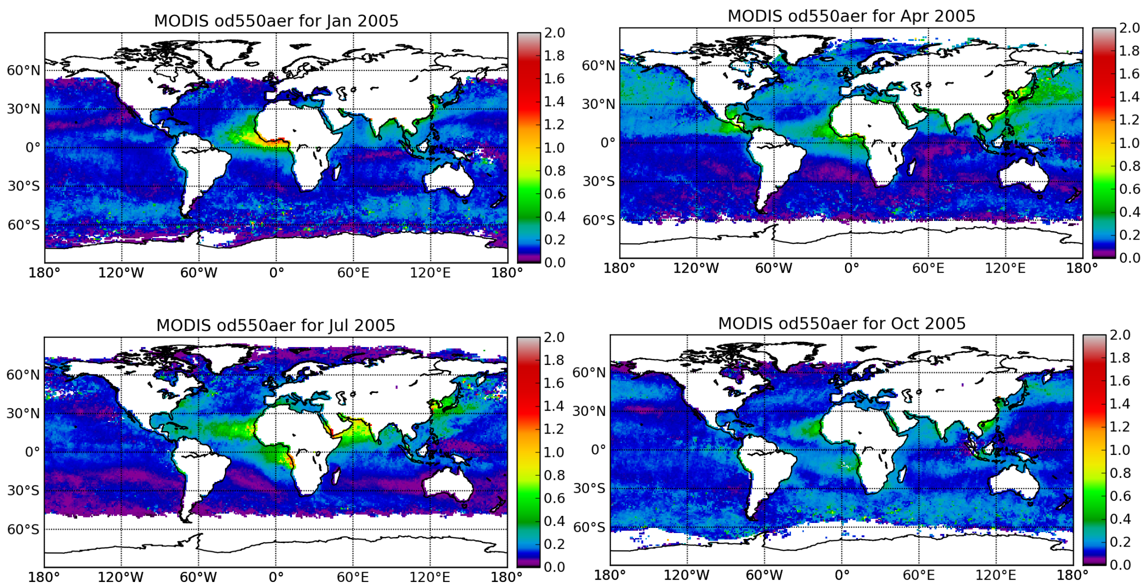

Figure 1. Monthly mean aerosol optical depth at 550 nm from Terra MODIS over the oceans for January, April, July and October 2005.

5.1 Monthly AOD Distribution Example

Sample monthly mean aerosol optical depth at 550 nm from MODIS Terra is shown in Fig. 1 for 4 months in 2005. The aerosol seasonal cycle is apparent, with Saharan dust plume peaking in the summer months, biomass burning being stronger in equatorial Africa in July. The continental outflow of anthropogenic aerosols in the Northern hemisphere reaches it peak in the spring and summer months. Movies with the monthly mean, standard deviation and number observations for each month in this dataset is available on-line at

ftp://gmaoftp.gsfc.nasa.gov/pub/data/dasilva/obs4MIPS/od550aer_MODIS_L3_C5/

5.2 Asynoptic Time Sampling

Because Terra satellite operates in a sun-synchronous polar orbit, it samples in the visible at relatively constant local solar time at each location (i.e., ~10:30 local at the equator) so it cannot resolve the diurnal cycle. In contrast, typical model monthly averaged outputs contain the averaged values over a time series of data within a fixed time interval (e.g. every 6 hours). For many constituents in the upper atmosphere, this difference is not likely a problem although for regions influenced by deep convection and its modulation of the diurnal cycle (e.g. tropical land masses), wildfire activity that tends to peak in the mid-afternoon, photochemical smog that can have one or two diurnal peaks, and other diurnal variability in natural and anthropogenic emissions, this time sampling bias should be considered.

5.3 Inhomogeneous

Sampling

Because the monthly averaged value in this MODIS data product is an average over observational data available in a given grid cell, the number of samples used for averaging varies with the geo-location of the cell. Because of the convergence of longitude lines near the poles, frequency, as well as the range of times-of-day when data are collected broadens as one moves from the equator toward either pole, with sampling at a given location as often as once every two days. Because the increased number of overpasses near the poles occurs over a broader portion of the diurnal cycle, this can affect the amplitude of the observed diurnal cycle in high-latitudes relative to the mid-latitudes and tropics. However, persistent cloudiness, a smaller-amplitude diurnal cycle in general, low sun-zenith angle, and polar night also affect high-latitude sampling. Therefore, the entire Terra MODIS data set cannot be treated as uniformly sampled at 10:30 local time.. The ancillary files with the observation count and standard deviations for each grid can be useful to quantify the inhomogeneous sampling of the dataset.

5.4 Clear-sky Sampling

Because MODIS (and all other total-column remote sensing) aerosol optical depth retrievals are only possible under clear sky conditions, there is the potential for a *Fair Weather Bias*. For hygroscopic aerosols, clear sky conditions are often associated with subsidence and lower values of relative humidity leading to smaller values of aerosol optical depth. Furthermore, clear-sky conditions following a rainstorm will be associated with reduced aerosol optical depth values due the wash out process induced by precipitation. Whenever possible, model aerosol optical estimates should take into consideration cloud fraction and humidity conditions within the clear portions of the grid-box.

6. Instrument Overview

Terra was launched on 18 December 1999, with data available from 24 February 2000, to present. MODIS is a 36-channel whiskbroom scanning radiometer. The channels (referred to as “bands” in the MODIS nomenclature) are distributed between 0.41 and 14.23 µm in four focal plane assemblies, with nadir spatial resolutions of 250 m (two bands), 500 m (five bands), and 1000m (29 bands). The 250 m bands are centered at 0.65 and 0.86 µm with the 500 m bands at 0.47, 0.55, 1.24, 1.63, and 2.11 µm. Each band’s spectral response is determined by an interference filter overlying a detector array imaging a 10 km along-track scene for each scan (i.e., 40, 20, and 10 element arrays for the 250, 500, and 1000-m bands, respectively). MODIS has several onboard instruments for in-orbit radiometric and spectral characterization.

MODIS scans a swath width sufficient for providing global coverage every two days from a polar-orbiting, sun-synchronous platform at an altitude of 705 km. Terra is in a descending orbit with an equatorial crossing of 1030 local solar time.

All MODIS atmosphere products are archived into two categories: pixel-level retrievals (referred to as Level–2 products) and global gridded statistics at a latitude and longitude resolution of 1 (Level–3 products). The Level-3 products are temporally aggregated into daily, eight-day, and monthly files containing a comprehensive set of statistics and probability distributions (marginal and joint).

Acknowledgements. Special thanks to the MODIS science and instrument teams.

7. References

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8. Useful Links

MODIS Atmosphere website: http://modis-atmos.gsfc.nasa.gov/
MODIS Aerosols: http://modis-atmos.gsfc.nasa.gov/MOD04_L2/index.html

MODIS On-line Data Archive: http://ladsweb.nascom.nasa.gov/

MODIS Algorithm Theoretical Basis Document:

http://modis-atmos.gsfc.nasa.gov/MOD04_L2/atbd.html

MODIS Atmosphere Team Publications: http://modis-atmos.gsfc.nasa.gov/reference/

9. Revision History

Rev 0 – 4/18/2013 – Initial release.