P1.25 MODIS CLOUD, AEROSOL, AND WATER VAPOR PRODUCTS FOR CLIMATE AND GLOBAL CHANGE STUDIES

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1. Introduction

For further understanding of the 'Total Earth System' and the effects of natural and human-induced changes on the global environment, the Moderate Resolution Imaging Spectroradiometer (MODIS) was launched aboard the Terra satellite on December 18, 1999 (10:30 am equator crossing time, descending node, Sun-synchronous near polar orbit) as part of NASA's Earth Observing System (EOS) mission. MODIS with its 2330 km viewing swath width provides almost daily global coverage. It acquires data in 36 high spectral resolution bands between 0.415 and 14.235 µm with spatial resolutions of 250 m (2 bands), 500 m (5 bands), and 1000 m (29 bands). This year a similar instrument will be flown on the EOS-Aqua satellite (1:30 pm equator crossing time, ascending node). This will enable us to study diurnal variation of the rapidly varying systems and will also provide us with a long term dataset for the same set of geophysical parameters for the study of climate and global change studies.

MODIS derived atmospheric and ocean products, including raw sensor counts, calibrated radiances, and geolocation products are archived at the Goddard Earth Sciences Data and Information Services Center Distributed Active Archive Center (GES DISC DAAC) and are freely made available (daac.gsfc.nasa.gov) to the public and scientific community.

In spite of the fact that current data products are of 'provisional' quality (validation activities and calibration algorithm enhancements are in progress), MODIS Science Team Members have shown that the quality of radiances and derived geophysical parameters are exceptionally good when compared to products derived from existing heritage sensors (AVHRR, GOES, Meteosat) and other in-situ observations. This presentation will provide highlights of the MODIS atmospheric products and demonstrate the quality of these products by presenting some examples of the MODIS atmospheric parameters.

2. Atmospheric Products

MODIS atmospheric products are available at two processing levels, level-2 and 3. Level-2 products contain orbital swath data, where as level-3 products contain global data that are averaged over time (daily, eight-day, monthly) over small equal angle grids (1^o x 1^o grid) called the Climate Modeling Grid (CMD). Table 1 gives the file size of these products.

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Brief details of these products are described below. The 36 spectral bands used in the retrieval of MODIS products are listed in Table 2.

More detailed information about these data products and the algorithms used to derive these products can be found in the respective Algorithm Theoretical Basis Documents (ATBDs). These documents as well as related current publications and presentations, are available from the MODIS atmospheric team web site (modis-atmos.gsfc.nasa.gov) or the Goddard DAAC web site (daac.gsfc.nasa.gov), where the data are archived.

Level-2 Atmospheric Products

There are five Level 2 atmospheric products:

- Atmospheric Aerosol *(MOD04_L2)*
- Total Precipitable Water Vapor *(MOD05_L2)*
- Cloud Properties *(MOD06_L2)*
- Atmospheric Profiles & Ozone *(MOD07_L2)*
- Cloud Mask *(MOD35_L2).*

These products contain atmospheric parameters in orbital swath format (pixel based spatial resolution). Because of large data volume, each file (granule) of a level-2 product contains observations of 5-minute duration (288 files for day and night data). In addition to standard key atmospheric parameters, these products also contain temporal, spatial & viewing geometry parameters (scan start time, latitude, longitude, solar & sensor zenith and azimuth angles), 48 bit based cloud mask information (presence of cloud, cloud shadow, sun glint, ice/snow, land/water, day/night), and extensive Quality Assurance (QA) information.

Level-3 Atmospheric Products

There are three Level-3 atmospheric products:

- Daily (*MOD08_D3*)
- Eight day (*MOD08_E3)*
- Monthly (*MOD08_M3*)

Each level-3 product is a global joint (aerosol, cloud, water vapor, ozone) product containing 1^o x 1^o grid averages and corresponding statistical parameters (uncertainty in derived parameters, minimum, maximum, number of pixels, histograms, correlation parameters, quality assurance weighted, and other statistically derived quantities) for almost all level-2 key atmospheric parameters. It should be noted that Eight-day averaging interval for product MOD08_E3 begins with the first day of MODIS data on Terra (Feb 25,

2000) and is not reset with the starting month or calendar year.

Table 1. Level 2 & Level 3 Atmospheric products

Processing Level	Spatial Resolution	Temporal Resolution	File Size	File Frequency
Level-2 (L2)	10 km, 5 km, 1 km, 250 m at nadir	5 minute	10-50 MB	144 or 288 files per day
Level-3 (L3)	1^o x 1^o equal angle grid	Daily, Eight Day, Monthly	410-800 MB	1 file per period

MODIS products are stored in the Hierarchical Data Format (HDF-EOS). In each product file, the parameters are written as Science Data Sets (SDS). To reduce file size, some parameters are scaled to integers. Scale factors and offset values are provided as SDS attributes to convert back to actual data values. The following equation may be used to convert stored values back to actual data:

data values = scale factor × (stored numbers – offset)

2.1 Aerosol Optical and Microphysical Properties (MOD04_L2) & (MOD08_D3, E3, M3)

MODIS aerosols are retrieved on a global scale. This is the first time that the aerosol is retrieved operationally over land in addition to ocean. Though there are separate algorithms for land (Kaufman et al. 1997) and ocean (Tanré et al. 1997), these two independent algorithms generate similar results (no discontinuity) at the coastal regions. Aerosol algorithms are based on 7 high spectral resolution solar bands (250 m & 500 m spatial resolution) compared to one or two wide bands of heritage sensors (AVHRR, GOES imager). Level-2 swath data are provided at a spatial resolution of 10 km at nadir. The MODIS data validation team has found that aerosol parameters compare very well with aerosol parameters retrieved from ground-based sun-photometers.

Key Aerosol and related Ancillary Parameters

Aerosol over Land & Ocean:
- Aerosol Optical Depth at 0.55 μm over Land and Ocean, and scattering angle

Aerosol over Land:
- Optical depth at 0.47 and 0.66 μm (based on continental aerosol model)
- Aerosol type (based on dynamic aerosol model)
- Corrected optical depths at 0.47, 0.55, 0.66 μm (based on dynamic aerosol model)
- Corrected optical depths at 0.47, 0.55, 0.66 μm for smoke, sulfate, dust aerosols
- Mass concentration (based on 0.66 μm), dust aerosol weighting factor
- Ångström exponent (based on 0.47 and 0.66 μm), Ångström exponents for smoke, sulfate, dust
- Radiation budget parameters: normalized surface reflectance (at 5 bands), atmospheric path radiances, and reflected & transmitted flux (at 0.47 and 0.66 μm)

Aerosol over Ocean:
- Effective optical depth at 7 bands (0.47, 0.55, 0.66, 0.87, 1.24, 1.64, 2.13 μm)
- Effective radius, mass concentration, cloud condensation nuclei (based on 0.55 μm)
- Aerosol optical depth for small and large particles
- Ratio: optical depth of small particles relative to effective optical depth (0.55 μm)
- Asymmetry factor & back scattering ratio at 7 bands
- Ångström exponents 1 (based on 0.55 and 0.865 μm) & 2 (based on 0.865 & 2.13 μm)
- Radiation budget parameters: normalized surface reflectance & spectral reflected and transmitted flux (at 7 bands)

Aerosol algorithm team members are: Yoram Kaufman, Didier Tanré, L. A. Remer, D. A. Chu, B. N. Holben, S. Mattoo, R. C. Levy, C. Ichoku, R. R. Li (NASA/GSFC, University of Lille, France)

2.2 Atmospheric Water Vapor (MOD05_L2) & (MOD08_D3, E3, M3)

MODIS is the first sensor to have near infrared bands within and around the 0.94 μm water vapor absorption band for estimating water vapor (Kaufman and Gao 1992). Five near-infrared bands (2, 5, 17, 18, and 19) are used to retrieve column water vapor in the daytime from reflective surfaces.

Key Water Vapor and related Ancillary Parameters:

- Near-infrared retrievals (1 km pixel resolution, daytime): Precipitable water vapor over clear sky land & bright ocean area (near sunglint), and over clouds (global), aerosol correction factor and QA parameters
- Infrared retrievals (5 km pixel resolution, day and night, clear sky, global) copied from MOD07_L2 product (MOD07_L2): Precipitable water vapor and QA parameters

Algorithm team members are: Near-IR algorithm - Bo-Cai Gao, Y. J. Kaufman, W. J. Wiscombe, R. R. Li (NRL & NASA/GSFC); IR-algorithm - Paul Menzel, L. E. Gumley (NOAA, Wisconsin)

2.3 Cloud Optical and Physical Properties (MOD06_L2) & (MOD08_D3, E3, M3)

Cloud optical thickness and effective particle radius are retrieved from *multi-wavelength* high spectral resolution solar bands (Nakajima and King 1990; King et al. 1992). The reflection function of clouds at water (or ice) absorbing bands in the near-infrared is primarily a function of cloud particle size, whereas the reflection function at non-absorbing bands is a function of cloud optical thickness. The cloud algorithm also uses the new band (1.375 μm) for detection of thin cirrus clouds

(Gao and Kaufman 1995), and for detection of polar clouds over snow. Cirrus clouds in polar regions are easily detected using MODIS data. Such cirrus detection is very difficult from NOAA AVHRR data due to the lack of narrow-band water vapor absorption bands on the AVHRR instruments. MODIS is also the first operational sensor containing three bands within the 8 to 12 µm region for differentiating cloud phase. It is also the first sensor to have CO_2 slicing bands at high spatial resolution (1 km) to retrieve cloud top parameters, compared to the same technique applied to its predecessors (HIRS) which has much larger footprints (18 km at nadir). Level-2 cloud optical parameters and cirrus parameters are at 1 km pixel resolution whereas cloud top parameters are at 5 km spatial resolution.

Key Cloud Optical & Microphysical and related Ancillary Parameters

- Cloud top parameters: Cloud top pressure, temperature, and effective emissivity (day, night, all)
- Cloud particle phase: Thermal & Near-infrared–based retrievals (day, night, all)
- Cloud optical thickness and effective radius (water, ice, water + ice, undetermined, all phases)
- Cloud water path (liquid, ice, liquid + ice, undetermined, all phases)
- Cloud fraction: Visible and SWIR based (cirrus, contrail, water, ice, water + ice, undetermined, all phases)
- Cloud fraction: IR-based (day, night, all)
- Cirrus cloud & contrail reflectance, spectral cloud forcing (5 bands), brightness temperature (7 bands)
- Surface temperature, surface type

Algorithm team members are: Michael D. King, Paul Menzel, Bo-Cai Gao, S. Platnick, R. A. Frey, M. A. Gray, P. Yang, S. C. Tsay, B. A. Baum, L. E. Gumley, W. L. Ridgway, E. G. Moody, P. A. Hubanks - (NASA/GSFC, UMBC, NRL, NOAA, U. Wisconsin)

2.4 Atmospheric Profiles, Ozone, Water Vapor and Stability Indices (MOD07_L2) & (MOD08D3, E3, M3)

Vertical Profiles of atmospheric temperature and moisture content, and ozone concentration are retrieved from multi-wavelength emitted thermal radiation measurements over clear sky scenes. Level-2 products are at 5 km pixel resolution.

Key Atmospheric State Parameters

- Temperature profiles: Retrieved & guess values at 20 levels, brightness temperature (12 bands)
- Humidity profiles: Retrieved & guess moisture values at 20 pressure levels, IR-based precipitable water vapor (lower & upper atmosphere and total)
- Geopotential height profile: Height values at 20 pressure levels, tropopause height
- Atmospheric stability indices: Total-totals, lifted index, K index
- Total ozone content (9.6 µm based)
- Secondary parameters: Surface elevation, surface pressure & temperature, cloud mask, and QA

Algorithm team members are: Paul Menzel, L. E. Gumley – NOAA /NESDIS, U. Wisconsin)

2.5 Cloud Mask (MOD35_L2)

For the first time, the cloud mask algorithm uses 11 spectral tests based on 17 narrow spectral bands (including the new 1.375 µm band) for identifying whether the scene is clear, cloudy or affected by shadows (Ackerman et al. 1998). SeaWiFS and MISR have no thermal bands for cloud screening. The smaller field of view of MODIS implies a higher probability of detecting clear sky pixels. The cloud mask provides information on clear-sky confidence level (high confident clear, probably clear, undecided, cloudy), identification of cirrus cloud, cloud shadow, sunglint, land/water, snow/ice, day/night, and numerous other test results at 250 m and 1 km pixel resolution.

Algorithm team members are: Paul Menzel, S. A. Ackerman, K. I. Strabala, R. A. Frey, B. A. Baum, C. C. Moeller, L. E. Gumley – NOAA/NESDIS, U. Wisconsin)

3. Other Related MODIS Products

Radiometrically Calibrated and Geolocated Radiance & Reflectance, and Geolocation products are much in demand by the atmospheric community (Ahmad et al. 2001).

- **MODIS (Level 1B) Radiance and Reflectance Products,** (**MOD02QKM, HKM, 1KM)**

The key parameters are: calibrated radiances, counts and uncertainty indices at 0.25, 0.5, and 1 km pixel resolution. Radiance algorithm team members are: V. V. Salomonson, W. L. Barnes, X. Xiong – NASA/GSFC

- **MODIS (Level 1A) Geolocation Product, 1 km pixel resolution (MOD03)**

The key Parameters are: Geodetic coordinates (latitude, longitude), ground elevation, solar & satellite zenith and azimuth angles, and land/sea mask. Geolocation algorithm team members are: V. V. Salomonson, E. J. Masuoka, R. J. Wolfe, A. J. Fleig, M. Nishihama, J. Kuyper

4. Validation Activities & Plans

Validation activities have been at high priority, and many field campaigns (involving aircraft, satellite overpasses, and in-situ surface measurements) were designed for testing MODIS algorithms (pre-launch activities), and for algorithm enhancement and data validation (post-launch field campaigns). Some of the major field campaigns and ongoing surface measurement networks are:

SCAR, WINTEX: 1995 - 1999
WISC-T2000: Oklahoma, Feb – Mar 2000

PRIDE:	Puerto Rico, June – July 2000
SAFARI 2000	Southern Africa, Aug – Sept 2000
TX-2001:	Oklahoma, Mar – Apr 2001
ACE-Asia:	Asia, Mar – May 2001, 2004
CLAMS:	US E. Coast, July – Aug 2001
CAMEX-4:	Florida Keys, Aug – Sept 2001
CLAP-2002:	Texas, March – April 2002
CRYSTAL-FACE:	Florida, July 2002
CRYSTAL-TWP:	Trop.W. Pacific July – Aug 2004

Surface Networks:
–AERONET, ARM, CIGSN, FARS, P-AERI, SMART, Balloon & Radiosonde

5. Data Production Status

The Goddard DAAC has been processing, archiving and distributing MODIS data since February 24, 2000. All MODIS products generated with preliminary calibration algorithms were assigned "beta status." These beta products were not of science quality, and were made available for evaluation purposes only. Calibration and validation efforts continued. By late Fall of 2000, many of the instrument calibration issues were resolved (Salomonson et al. 2001). The data processed using improved calibration algorithms were given "provisional status." Beta release is referred to as Version-1 and provisional release as Version-3 (there are no Version-2 products). The provisional release Version-3 data products show significant improvements over the Version-1 products. These products also compare well with coincident ground and aircraft-based observations acquired during several field campaigns (WISC-T2000, PRIDE, SAFARI-2000, and TX-2001) designed for MODIS data validation.

6. Data Access

MODIS atmosphere and ocean products, including calibrated radiances and geolocation, are archived at the NASA Goddard DAAC (daac.gsfc.nasa.gov) and are freely made available to the public and science user communities. To facilitate data access, a user-friendly web-based search and order system (with simple point & click buttons for selections from the world map and data calendar) has been developed by the Goddard DAAC MODIS Data Support Team (MDST).

The MDST provides expert assistance to the user (modis@daac.gsfc.nasa.gov) in the areas of accessing data products, documentation, browse, and data analysis (Leptoukh et al. 2001). For user convenience, on-demand subsetting is also provided. Several data manipulation, re-projection, subsetting, and visualization tools developed by MDST (daac.gsfc.nasa.gov/CAMPAIGN_DOCS/MODIS/software.shtml) and the MODIS atmosphere science team (modis-atmos.gsfc.nasa.gov/tools.html) have been made available to the Earth science community. These data tools have the capability of displaying and extracting specific parameters and spatial subsets of MODIS data (from large MODIS files in HDF-EOS format) and saving them as binary, ASCII, or image files.

The entire suite of MODIS products (including products from other Terra sensors) can also be searched and ordered from all NASA DAACs and NASA affiliated centers via the NASA EOS Data Gateway (EDG) at eos.nasa.gov/imswelcome.

7. Applications

MODIS atmospheric products provide almost all key atmospheric parameters (such as cloud and aerosol characteristics, vertical distribution of temperature and humidity, atmospheric ozone, total precipitable water vapor) that are being used by scientists from a variety of disciplines, including oceanography, biology, and atmospheric sciences to predict and monitor changes in global and regional phenomena. Aerosol, water vapor, and cloud information will be very useful in developing global climatologies, corrections of remotely sensed surface features for atmospheric contributions, understanding of aerosols and cloud interactions, sources and sinks of specific aerosol types (e.g., sulfates and biomass-burning aerosols), investigation of seasonal and inter-annual changes of aerosol, cloud types, water vapor, ozone and atmospheric states, in addition to its use in weather prediction and data assimilation models.

8. Summary

The strengths of MODIS include its global coverage, high radiometric resolution, appropriate dynamic ranges, and accurate calibration in reflective and thermal infrared bands (Barnes et al., 1998) designed for retrievals of atmospheric, land and sea surface properties. Even though data validation activities are still in progress, the provisional radiometric calibrated radiance and reflectance, and derived products (Version-3) show very fine details and exceed expectations when compared to in-situ observations. Almost one year of consistent data derived from radiances processed using an improved calibration algorithm (Version-3) is available to the public and science user community. These high radiometric accuracy measurements can be used by the scientific community to detect subtle signatures of climate change, study regional and global phenomena, and for predictions and characterization of natural disasters. MODIS atmospheric and ocean derived products, including calibrated radiance and reflectance, and geolocation products, are archived at the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) Distributed Active Archive Center (DAAC) and are freely available (daac.gsfc.nasa.gov/CAMPAIGN_ DOCS/MODIS) to the scientific and other data user communities.

9. Acknowledgements

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Table 2. MODIS Spectral Bands

Band	μm	Bandwidth	Use
Reflective Solar Bands (250 m spatial resolution)			
1	0.659	0.620 - 0.670	aerosol, cloud, land
2	0.865	0.841 - 0.876	
Reflective Solar Bands (500 m spatial resolution)			
3	0.470	0.459 - 0.479	Aerosol & cloud optical thickness, cloud phase, cloud effective radius, cloud mask, snow, land
4	0.555	0.545 - 0.565	
5	1.240	1.230 - 1.250	
6	1.640	1.628 - 1.652	
7	2.130	2.105 - 2.155	
Reflective Solar Bands (1 km spatial resolution)			
8	0.412	0.405 - 0.420	Ocean color chlorophyll phytoplankton biogeochemistry
9	0.443	0.438 - 0.448	
10	0.488	0.483 - 0.493	
11	0.531	0.526 - 0.536	
12	0.551	0.546 - 0.556	sediments, atmosphere
13	0.667	0.662 - 0.672	
14	0.678	0.673 - 0.683	fluorescence
15	0.748	0.743 - 0.753	atmosphere, aerosol
16	0.869	0.862 - 0.877	
17	0.905	0.890 - 0.920	atmospheric total precipitable water vapor
18	0.936	0.931 - 0.941	
19	0.940	0.915 - 0.965	
26	1.375	1.360 - 1.390	cirrus cloud
MWIR Thermal Emissive Bands (1 km spatial resolution)			
20	3.75	3.660 - 3.840	cloud & surface, temperature, fire & volcano, sea surface temperature
21	3.96	3.929 - 3.989	
22	3.96	3.929 - 3.989	
23	4.05	4.020 - 4.080	
24	4.47	4.433 - 4.498	atmospheric temperature profile
25	4.52	4.482 - 4.549	
LWIR Thermal Emissive Bands (1 km spatial resolution)			
27	6.72	6.535 - 6.895	tropospheric water vapor
28	7.33	7.175 - 7.475	
29	8.55	8.400 - 8.700	cloud particle radius
30	9.73	9.580 - 9.880	total column ozone
31	11.03	10.780 -11.280	cloud, surface temperature, fire
32	12.02	11.770 -12.270	
33	13.34	13.185 -13.485	cloud top height, temperature, pressure, temperature profile
34	13.64	13.485 -13.785	
35	13.94	13.785 -14.085	
36	14.24	14.085 -14.385	