APPENDIX A

1. OVERVIEW OF MODIS INSTRUMENT

The Moderate Resolution Imaging Spectrometer (MODIS) scientific instrument is part of the NASA Earth observing System (EOS) mission. MODIS was launched onboard the Terra and Aqua satellites in December 1999 and May 2002 respectively. Both satellites have been working well except for band 6 (1.628 µm – 1.652 µm) of the Aqua satellite which is either non-functional or noisy. The MODIS instrument provides calibrated high radiometric sensitivity (12 bit) in 36 spectral bands covering wavelengths from 0.4 µm to 14.4 µm in the visible (VIS), near infrared (NIR), short and mid-wave infrared (SMIR), and long-wave infrared (LWIR). Furthermore, the MODIS sensor has three different nadir ground spatial resolutions: 250m (bands 1 - 2), 500m (bands 3 - 7), and 1000m (bands 8 - 36) Table 1 provides some information on the MODIS bands and their useage. In the long track direction, there are 40 detectors per band for bands 1 - 2, 20 detectors per band for bands 3 - 7, and 10 detectors per band for bands 8 - 36[1]. A double-sided scan mirror providing ±55-degree scanning pattern at the EOS orbit of 705 km achieves a 2,330-km swath and provides near-daily imaging capability, complementing the spectral, spatial, and temporal coverage of the other research instruments [2]. MODIS data will improve understanding of global dynamics and processes occurring on the land, in the oceans, and in the lower atmosphere [3]. The Terra satellite orbits around the Earth from north to south, crossing the equator in the morning, while the Aqua satellite orbits the earth from south to north crossing the equator in the afternoon. MODIS data are transferred to ground stations in White Sands, New Mexico, and then sent to the Data and Operation System (EOS) at the Goddard Space Flight Centre. The MODIS instrument has been designed to provide improved monitoring for land, ocean, and atmosphere research. Spectral channels for improved atmospheric and cloud characterization have been included to permit both the removal of atmospheric effects on surface observations and the provision of atmospheric measurements [2].

Table 1 Properties of the MODIS bands

Band	Wavelength (nm)	Resolution (m)	Key Use	Primary nature
1	620-670	250	Absolute Land Cover Transformation, Vegetation Chlorophyll	Reflectance Solar Bands
2	841-876	250	Cloud Amount, Vegetation Land Cover Transformation	
3	459-479	500	Soil/Vegetation Differences	
4	545-565	500	Green Vegetation	
5	1230-1250	500	Leaf/Canopy Differences	
6	1628-1652	500	Snow/Cloud Differences	
7	2105-2155	500	Cloud Properties, Land Properties	
8	405-420	1000	Chlorophyll	
9	438-448	1000	Chlorophyll	
10	483-493	1000	Chlorophyll	
11	526-536	1000	Chlorophyll	
12	546-556	1000	Sediments	
13h	662-672	1000	Atmosphere, Sediments	
13l	662-672	1000	Atmosphere, Sediments	
14h	673-683	1000	Chlorophyll Fluorescence	
14l	673-683	1000	Chlorophyll Fluorescence	
15	743-753	1000	Aerosol Properties	
16	862-877	1000	Aerosol Properties, Atmospheric Properties	
17	890-920	1000	Atmospheric Properties, Cloud Properties	
18	931-941	1000	Atmospheric Properties, Cloud Properties	
19	915-965	1000	Atmospheric Properties, Cloud Properties	
Band	**Wavelength (µm)**	**Resolution (m)**	**Key Use**	**Primary nature**
20	3.660-3.840	1000	Sea Surface Temperature	Thermal Emissive Bands
21	3.929-3.989	1000	Forest Fires & Volcanoes	
22	3.929-3.989	1000	Cloud Temperature, Surface Temperature	
23	4.020-4.080	1000	Cloud Temperature, Surface Temperature	
24	4.433-4.498	1000	Cloud Fraction, Troposphere Temperature	
25	4.482-4.549	1000	Cloud Fraction, Troposphere	

			Temperature	
26	1.360-1.390	1000	Cloud Fraction (Thin Cirrus), Troposphere Temp.	Reflectance Solar Band
27	6.535-6.895	1000	Mid Troposphere Humidity	Thermal Emissive Bands
28	7.175-7.475	1000	Upper Troposphere Humidity	
29	8.400-8.700	1000	Surface Temperature	
30	9.580-9.880	1000	Total Ozone	
31	10.780-11.280	1000	Cloud Temperature, Forest Fires & Volcanoes, Surface Temp.	
32	11.770-12.270	1000	Cloud Height, Forest Fires & Volcanoes, Surface Temperature	
33	13.185-13.485	1000	Cloud Fraction, Cloud Height	
34	13.485-13.785	1000	Cloud Fraction, Cloud Height	
35	13.785-14.085	1000	Cloud Fraction, Cloud Height	
36	14.085-14.385	1000	Cloud Fraction, Cloud Height	

1.1 MODIS SUBSYSTEMS

The MODIS instrument has been designed with subsystems shown in Figure 1.

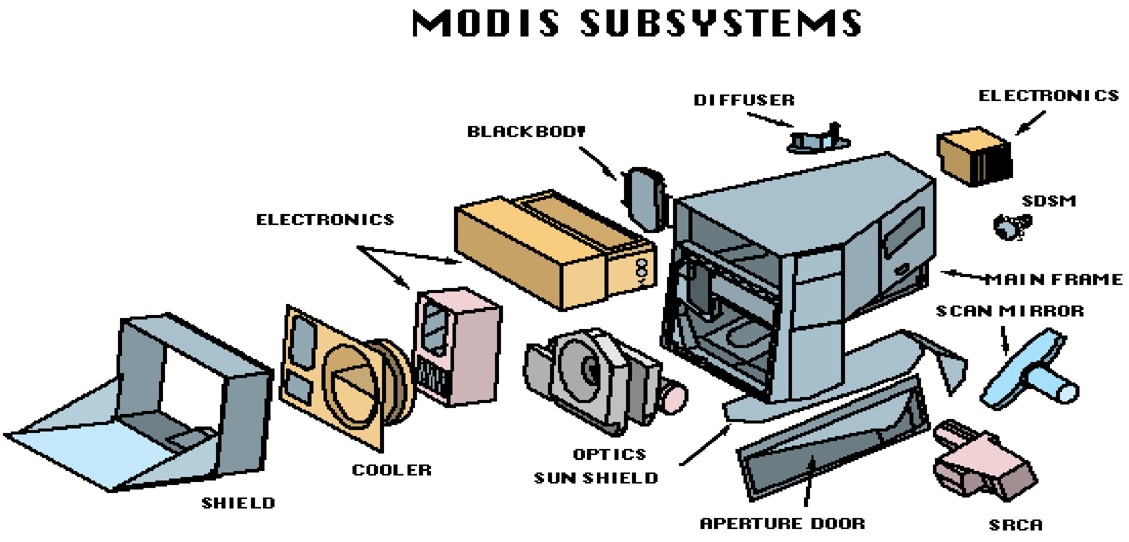

Figure 1 MODOS Subsystems[4]

1.1.1. ON-BOARD CALIBRATION SYSTEM

The MODIS instrument has a full complement of four On-Board Calibrators (OBCs) that produce radiometric, spectral, and spatial calibration for various MODIS components.

- **Blackbody Assembly (BB)**

Surfaces of the Earth and clouds emit thermal photons by virtue of their temperatures and these photons may be used to estimate the temperatures of these objects when viewed in the medial and long wave infrared wavelengths (MWIR and LWIR). The MODIS team use emission from a Blackbody (BB) to help standardize the thermal bands, which are one of the features of MODIS. An ideal BB is non-reflective (perfect absorber and emitter) and when MODIS measures the photon power of at a particular wavelength when looking at a BB, its temperature can be exactly determined. A full opening radiometric calibration source of the MWIR and LWIR bands is provided by the BB assembly to produce 1 percent absolute accuracy. The BB assembly provides known radiance levels and is also used in the DC restore operation (a space-view signal level provides the second level for all bands in the two-point calibration). The BB is designed with v-grooves cut at an included angle of approximately 45 degrees, which presents excellent performance in a compact package [5, 6]. It provides an excellent temperature uniformity and a high effective emissivity greater than 0.992 enabling an absolute calibration to be achieved.

- **Solar Diffuser (SD)**

The Solar Diffuser is used to calibrate 20 MODIS reflective solar bands [7]. The signals in these bands are a consequence of the reflectance properties of the Diffuser's surface and the sun's angle when radiation strikes it. A source for the absolute radiometric calibration of the reflective bands was provided by MODIS scientists by predicting the radiance of the diffuser struck by Sunlight once per orbit. The data are collected when the instrument is on the dark side of the terminator, to limit the level of stray light entering MODIS via the Earth View port [5, 6].

- **Solar Diffuser Stability Monitor (SDSM)**

The purpose of the SDSM is to monitor degradation of the SD through its lifetime using 9 individually filtered detectors and measuring the responses of the SD view and the direct Sun view through a screen of 1.44% nominal transmittance [7]. Table 2 lists the SDSM detectors used and their corresponding MODIS bands and wavelengths [6].

Table 2 MODIS bands and their corresponding wavelengths and solar diffuser stability monitor (SDSM) detectors

MODIS Band	Wavelength (nm)	SDSM Detector
1	646.1	D5
2	856.5	D7
3	465.7	D3
4	553.8	D4
8	412.0	D1
11	529.7	D3
15	746.6	D6
17	904.3	D8
19	936.2	D9

- **Spectroradiometric Calibration Assembly (SRCA)**

The Spectroradiometric Calibration Assembly (SRCA) is the MODIS calibration device designed for monitoring the visible (VIS), near infrared (NIR), and short-wave infrared (SWIR) bands. Furthermore, SRCA generates band-to-band registration information in-orbit for all 36 spectral bands at the same time that MODIS is collecting and recording spectral data [5].

1.1.2. DOOR ASSEMBLIES

The MODIS instrument has three doors (Earth, Space, and Solar view doors) with the purpose of protecting the internal components from dirt and breakage. Furthermore, in some cases these doors are used to help the instrument's self-calibration processes.

- **Earth View Door**

The Earth-view door (Nadir Aperture Door or NAD) that covers the opening in MODIS that faces Earth's surfaces and helps MODIS data to remain free of contamination from optical scatter is generally kept open. Sometimes the door is closed to avoid any data inflowing to the instrument, usually when the instrument or satellite is in safe-mode. The door is painted black inside to reduce radiation scatter, whereas the outside is painted white to assist management of instrument temperature [6].

- **Space View Door**

The Space view door (SVD) covers the opening that faces space. This door has two functions; for reduce data contamination and to protect the Radiative Cooler from Earth's energy. The door's inner surface is designed to reduce the intermediate-stage radiator's field of view to cold space to avoid data contamination from other radiant energy sources. The outside of the SVD is painted white for thermal control. The panels of this door are made using a honeycomb pattern to keep this large door's weight down [6].

- **Solar View Door**

The Solar-view door (Solar Diffuser Door or SDD) covers the opening in MODIS that faces the Sun. This door also has an optical screen that works independently of the door to allow the Solar Diffuser to obtain varying amounts of solar energy. The SDD and the screen also cover the opening to the Solar Diffuser Stability Monitor (SDSM). The SDD and screen can both be open or closed, or the door open and the screen closed which is the most common situation because it allows a compromise between contamination control and calibration. This door is also made from a honeycomb pattern to keep the overall weight low [6].

1.1.3. MAIN ELECTRONICS MODULE (MEM)

The Main Electronics Module (MEM) is used for the controlling of the format engine, the instrument, and the Scan Mirror's rotation. The format engine operates under the control of a 12-MHz MIL-STD 1750A format processor which performs storage, reorganization, and averaging functions in real time. The format engine can be completely reprogrammed in flight. The format engine also processes a particular scene-pixel from all 36 MODIS bands to be contained within the same Consultative Committee for Space Data Systems CCSDS packet[6].

1.1.4. ELECTRONICS SYSTEM

The Electronics System was designed to perform all jobs that could not be achieved by the Main Electronics Module (MRM) and to provide the highest operational versatility and performance combined with long life. Most functions, including calibration, are performed under internal processor control in response to time-tagged commands from the spacecraft. All formats, operational sequences, and algorithms can be modified by reprogramming the processors from the ground. The Electronics System carries out many of functions such as presenting clocks and bias voltages to all four Focal Plane Assemblies (FPAs)s, also detecting, pre-processing, converting data to 12bit digital words, assembling scene radiances into CCSDS packets, controlling Scan Mirror rotation, controlling the motion of eleven other mechanisms, controlling temperatures on the Focal Planes and in the calibrators to stabilize detector performance, receiving and executing commands and providing telemetry via the MIL-STD 1553B interface [6].

1.1.5. FOCAL PLANE ASSEMBLIES

The Focal Plane Assemblies (FPAs) includes 36 distinct spectral bands divided into four separate FPAs: Visible (VIS), Near Infrared (NIR), Short- and Mid-Wave Infrared (SWIR/MWIR), and Long-Wave Infrared (LWIR). Each FPA concentrate onto concentrate a specific section of detector pixels that are fairly large of size ranging from 135µm to 540 µm square. The values generated from these pixel are what scientists use for studying and the Earth's land and water surfaces and atmosphere [6].

1.1.6. SPACE VIEWING ANALOG MODULE

The Space-Viewing Analog Module (SAM) carries out many of tasks to help the MODIS instrument keep its data accurate and this includes reading and processing data from bands 1 - 30, converting and sending data to the format engine, ensuring the image is perfectly registered in the event of a mechanical shift, converting the processed data into 12-bit numbers and sending it to the format engine. Furthermore, SAM uses data from the space and blackbody views to calculate and update correction coefficients. SAM offers 14 low-noise clocks to keep from interfering with MODIS data collection and enables programmable voltages to each Focal Plane. Finally, SAM manages the charge injection circuit integrated into the Focal Plane readouts [6].

1.1.7. FORWARD-VIEWING ANALOG MODULE

The Forward-Viewing Analog Module (FAM) converts signals from bands 31 - 36 into the input range of the *analog-to-digital* (A/D) converter. These bands are used for creating Cloud and Surface Temperature and Cloud Top Attitude. The wavelengths of these bands range from 10.78 to 14.385 μm[6].

1.1.8. MAINFRAME

The Mainframe is the main structural component of the MODIS instrument. It includes all the internal components of the instrument which are: the telescope, Aft optics, Scan Mirror, Passive Radiative Cooler, four calibration assemblies, three anti-contamination doors and three kinematic mounts which anchor the Mainframe to the satellite [6].

1.1.9. OPTICAL SYSTEM

The Optical System gathers, directs and splits the radiation from the Earth into the 36 spectral bands on which MODIS focuses. The Optical System is the core of the MODIS instrument and consists of fourteen components: the Afocal Telescope, Scan Mirror, Fold Mirror, Afocal Gregorian Telescope, field stop, Dichroic Housing, Secondary Mirror, three Dichroic Beamsplitters and four Focal Plane Assemblies (FPAs) [6].

1.1.10. PASSIVE RADIATIVE COOLER

The Passive Radiative Cooler is made from aluminum, Kel-F, magnesium, Invar, glass-epoxy thermal isolators and stainless steel. The Passive Radiative Cooler is designed to cool the Long-wave and the Short/Mid-wave Focal Plane Assemblies to 83K, however, 136mW of power will be rejected by the Passive Radiative Cooler.The Passive Radiative Cooler is a three-stage unit weighing 11 kilograms [6] and is shown in Figure.

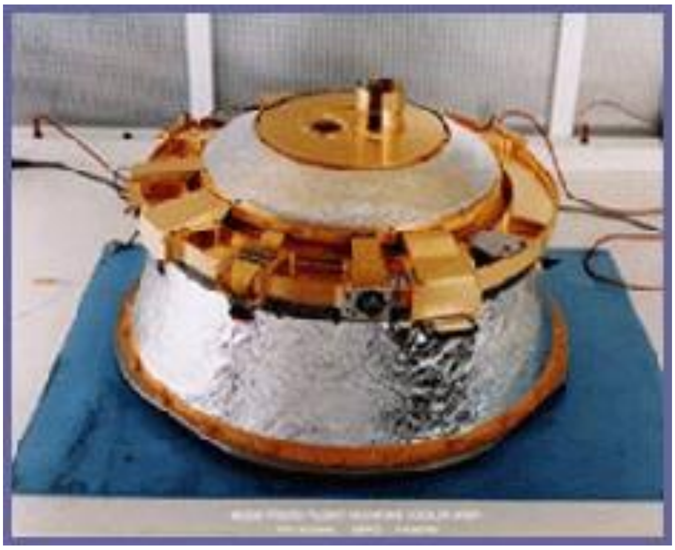

Figure 2 Passive Radiative Cooler[8]

1.1.11. Optical Bench Assembly

The graphite-epoxy matched set which includes the Aft Optics Platform (AOP) and the Afocal Telescope Bench (ATB) is the primary load-carrying structure for the Optical Bench Assembly that provides optically accurate positioning of the four objective assemblies and the dichroic assembly. It also uses three titanium anchors to provide the mounting plane for the Passive Radiative Cooler. The ATB provides accurate registration of the primary, secondary, and fold telescope mirrors relative to each other and a close-tolerance three-point mount for the AOP, which aligns the aft optics to the telescope. Optical alignments are of the order of 25µm. The weight of the Optical Bench Assembly is 22 kg [6].

1.1.12. OPTO-MECHANICAL SYSTEM

The Opto-Mechanical System uses a design technique that maximizes the modularity of the MODIS instrument to allow parallel fabrication, construction and testing of the Mainframe, Scan Mirror, Passive Radiative Cooler, Optical Bench, and the Door Assemblies which are the principal components.

By confirming that each sub-assembly met the requirements of the system before being integrated into a cohesive instrument, the modular instrument construction provided the most efficient system to integrate and test at the same time, before launching the system into orbit where it would be too late to make mechanical changes [6].

1.1.13. SCAN MIRROR

The Scan Mirror directs light from the surface of the Earth to the Focal Plane Assembly making it one of the most critical MODIS components. It is important that the two sides of the scan mirror be free from defects and be close to identical surfaces to ensure great accuracy of MODIS data [6].

1.2 MODIS PRODUCTS AND APPLICATIONS

From the raw data, MODIS provides over 40 standard data products, in the Hierarchical Data Format – Earth Observing System (HDF-EOS) [9], intended to help scientists studying Earth's land, ocean and atmosphere [10]. MODIS data have several levels of maturity. Scientists have used MODIS products in a great variety of applications, including oceanography, biology, and atmospheric science. The next section provides some details of each individual product whose names start with MO or MY for Terra and Aqua satellites respectively [11].

1.2.1. MODIS CALIBRATION PRODUCTS

MODIS Calibration products (Level 1A, Level 1B and geo-location) are a precursor to every geophysical science product [12].

- ***Level-1A Radiance Counts (MOD01, MYD01)***

  MODIS Level 1A data is produced by the MODIS Adaptive processing System (MODAPS) and sent to Level 1 and Atmosphere

Archive and Distribution System (LAADS) (http://modis.gsfc.nasa.gov/data/). Level 1A processing includes packaged and reformatted row instrument data from Level 0 MODIS data received from the EOS data and operating system (EDOS) [13]. Row Radiance Counts data set includes Level 1A Swath (MOD01 or MYD01) data, row instrument engineering and spacecraft ephemeris data for all 36 MODIS channels, which is used as input for geo-location, calibration, and processing. For indicating missing or bad pixels and instrument modes quality indicators have been added. This product includes all MODIS digitized (counts) data for all bands, spatial resolutions, time covered, all detector views, and all engineering and ancillary data [11]. MODIS scan data during Level 1A processing includes eight fields which are used to store the earth location information for each MODIS spatial element. These fields are: geodetic latitude, geodetic longitude, height above the Earth ellipsoid, satellite zenith angle, satellite azimuth, range to the satellite, solar zenith angle and solar azimuth [13].

- ***Level – 1B Calibrated Geo-located Radiances***

MODIS Level 1A sensor counts (MOD 01) are used to generate, calibrated and geo-located radiances (in W/(m^2.µm.sr)) for 36 bands and presented as Level 1B data. MODIS Level 1B calibration code generates four product files: Calibrated Earth View data at 250m resolution MOD02QKM and MOD02QKM for Terra and Aqua respectively; Calibrated Earth View data at 500m resolution including the 250m resolution bands aggregated to 500m resolution MOD02HKM and MOD02HKM for Terra and Aqua respectively; Calibrated Earth View data at 1km resolution including the 250m and 500m resolution bands aggregated to 1km resolution MOD021KM and MOD021KM for Terra and Aqua respectively; and On Board Calibrator (OBC) and Engineering Data MOD02OBC and MYD02OBC for Terra and Aqua respectively which contains on board measurements in the Space View, Black Body, Spectro-Radiometric Calibration Assembly and Solar Diffuser Sectors, and additional engineering data[14]. The reflectance and the radiance can be generated from the solar reflective bands (1-19 and 26) using of the Level 1B scaled integer representation. Quality flags, error estimates, and calibration data are all provided in Level 1B data files. Also, Brightness Temperature (BT) data can be generated using thermal emissive bands (20-25 and 27-36) [6, 15].

- ***Geolocation Data***

MODIS Geolocation product (MOD03) consists of information on geodetic coordinates (latitude, longitude, and height), and the sun and satellite sensors properties (sensor zenith angles, sensor azimuth angles, slant ranges, solar zenith angle, solar azimuth angles) and geolocation flag values for each MODIS 1-km sample. By comparison, MODIS level 1B 250m and 500m data sample include just information about latitude and longitude. Spacecraft attitude and orbit, instrument telemetry, and a digital elevation model are used to determine the geolocation fields [16].

1.2.2. MODIS ATMOSPHERIC PRODUCTS

MODIS atmospheric products include five data products in Level 2 and three data products in Level 3. The level 2 products contain geophysical parameters for aerosols (optical properties and mass concentration), water vapour, clouds (physical and optical properties), atmospheric profiles (temperature, moisture and total ozone and stability indices) and cloud mask. The Level 3 products contain daily, weekly and monthly statistics for the Level 2 science parameters [17]. MODIS Atmospheric algorithm using twenty six MODIS bands to create atmospheric products [18]. Figure 3 summarises the MODIS atmosphere data processing architecture and products.

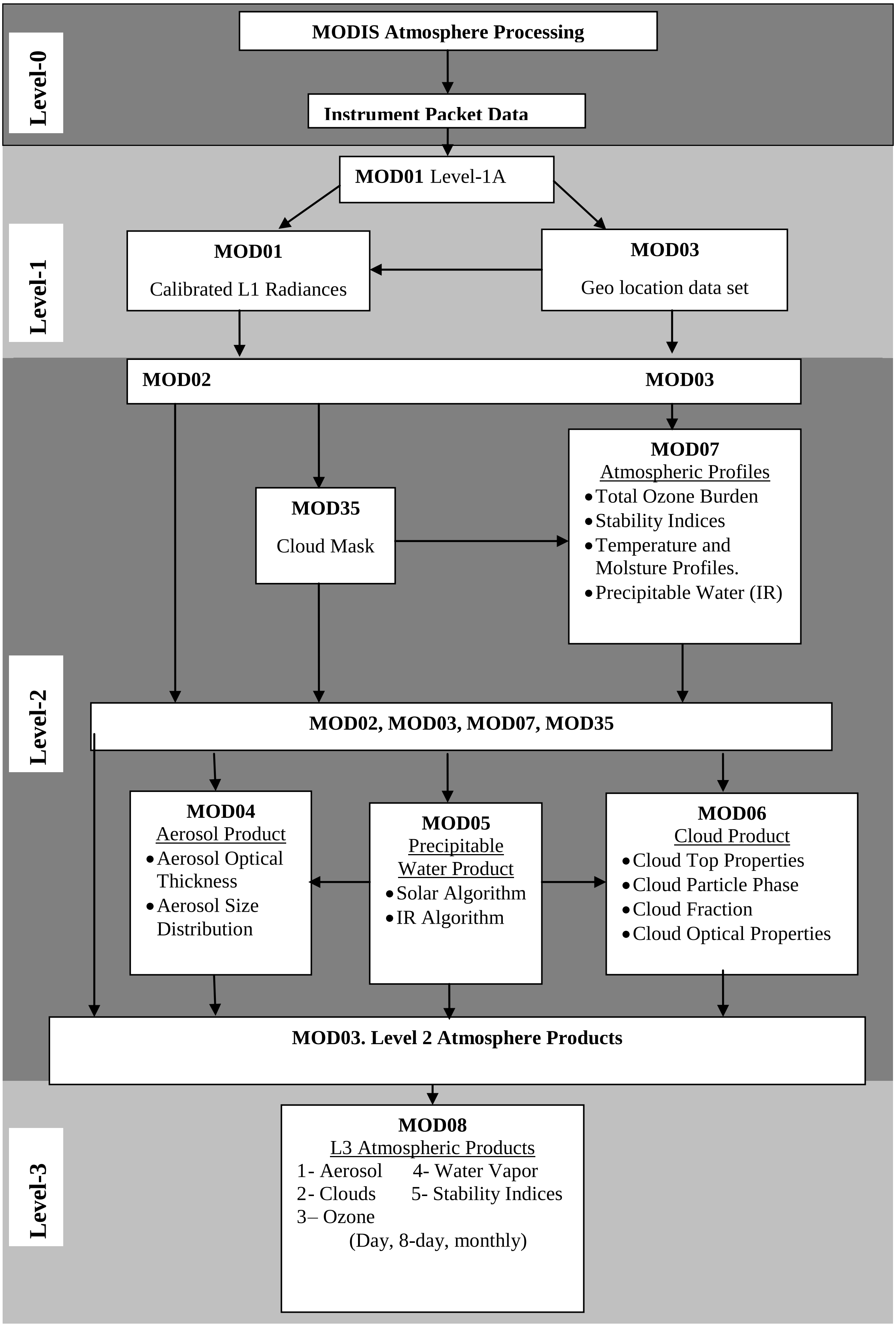

Figure 3 MODIS atmosphere data processing architecture and products[18].

- ***Aerosol product (****MOD04 for Terra and MYD04 for Aqua****)***

MODIS Aerosol Algorithm retrieves daily Level 2 Aerosol parameters at a 10-km spatial resolution from the (MODIS) daytime data. These aerosol parameters consist of aerosol optical thickness (AOT) at 0.47, 0.55 and 0.66 μm wavelengths produced over land, and at 0.47, 0.55, 0.66, 0.87, 1.2, 1.6, and 2.1 μm produced over ocean; Angstrom exponent produced over land and ocean; while the effective radii and the fraction of AOT contributed by the small size mode produced over ocean. MODIS Level 2 aerosol products are used to generate Level 3 aerosol products at global daily, weekly, eight day and monthly intervals [19].

- ***Total Precipitable Water Vapour (****MOD05 for Terra and MYD05 for Aqua****)***

MODIS has five near-infrared bands positioned near the 0.94μm water vapour band for the remote sensing of water vapour column amounts over clear land areas and over oceanic areas with sun-glint. The retrieval algorithm relies on observations of water vapour absorption of near-infrared solar radiation reflected by the bottom surface. The transmittance used the table look-up procedure to derive water vapour column amounts and is applied to every 1-km pixel. The lookup tables were pre-calculated using a line-by-line atmospheric transmittance code and the HITRAN2000 spectroscopic database. There are about 7% errors determined from water vapour values when it uses the near-infrared algorithm comparing with water vapour measurements using ground-based microwave radiometers. High-resolution estimates from MODIS of total precipitable water can be useful in predicting the distribution of rainfall patterns. The near-infrared observations provide unique coverage with the near-infrared 1-km total precipitable water (TPW) product providing TPW details over land and sun-glint regions of the ocean during the day and the thermal infrared 5-km TPW product provides TPW information over land and ocean during both day and night under clear skies. The near-infrared TPW includes a quality assurance parameter to specify whether the pixel is clear or cloudy [18].

- ***Cloud Product (****MOD06 for Terra and MYD06 for Aqua****)***

The cloud product (MOD06) algorithm uses infrared and visible techniques to monitor the physical, radiative, and microphysical properties of clouds. Cloud optical thickness and effective radius are generated for six visible and near-infrared bands at 1km spatial resolution. Cloud-top properties, including cloud-top temperature, cloud-top pressure, and effective emissivity, are produced using the infrared split window and long wave CO absorption bands for both day and night times at 5km spatial resolution. Cloud thermodynamic phase at 5km resolution using a two-band algorithm that includes an additional thermal band at 8.55μm, and also at 1km resolution using a different technique based on results from the cloud mask tests followed by a bi-spectral threshold test, shortwave infrared tests, and finally cloud-top temperature [20]. Finally, the cloud product includes a cirrus reflectance product at a visible wavelength to use for separate cirrus scattering effects from the land surface. Thus, the cloud product comprise many different cloud properties generated from 14 bands, and the file size during the day when additional 1km resolution products are included is higher than at night when it contains only cloud-top properties and thermodynamic phase at 5-km resolution [18].

- ***Atmospheric Profiles (****MOD07 for Terra and MYD07for Aqua****)***

The atmospheric profiles (MOD07) algorithm is a statistical regression that uses 12 long wave infrared bands with wavelengths between 4.47μm (band 24) and 14.24μm (band 36) [18]. The atmospheric profiles product provides estimates total column tropospheric and stratospheric ozone, atmosphere profiles of moisture and temperature, atmospheric stability indexes, and total tropospheric column water vapour. [9, 18]. The clear-sky radiances measured by MODIS over land and ocean for both day and night are used in the retrieval algorithm. The MODIS cloud mask algorithm is used to identify cloud free pixels. MODIS temperature and moisture products can be used for determination and validation of some MODIS products such as sea and land surface temperature, and ocean aerosol properties [21].

- ***Gridded Atmospheric Product (****MOD08 for Terra and MYD08 for Aqua****)***

Level-3 atmosphere products (MOD08) include three products: MOD08_D3 (daily), MOD08_E3 (every eight days), and MOD08_M3 (monthly), each covering a different time and containing statistics derived from the four Level-2 atmosphere products: MOD04_L2, MOD05_L2, MOD06_L2, and MOD07_L2. The daily product contains approximately 600 statistical datasets while eight-day and monthly products have nearly 800 statistical datasets derived from approximately 80 scientific parameters from the four Level-2 products. The eight-day and monthly products have the same format and larger size than the daily product [18].

- ***Cloud Mask (****MOD35 for Terra and MYD35 for Aqua****)***

The goal of the cloud mask (MOD35) algorithm is to classify each pixel as confidently clear, probably clear, probably cloudy, or cloudy. The cloud mask is generated at 250m and 1000m resolutions [22]. The cloud mask consists of 48 bits of output that include information on individual cloud test results. However, there is no need to process all 48 bits when applying the mask; only the first 8 bits of the mask may be necessary. Figure 5 B shows an example of cloud mask of MODIS image captured by Aqua satellite over North Africa on 2005 where the red flag pixel is confidently clear, yellow is probably clear, light blue is probably cloud and dark blue is cloud.

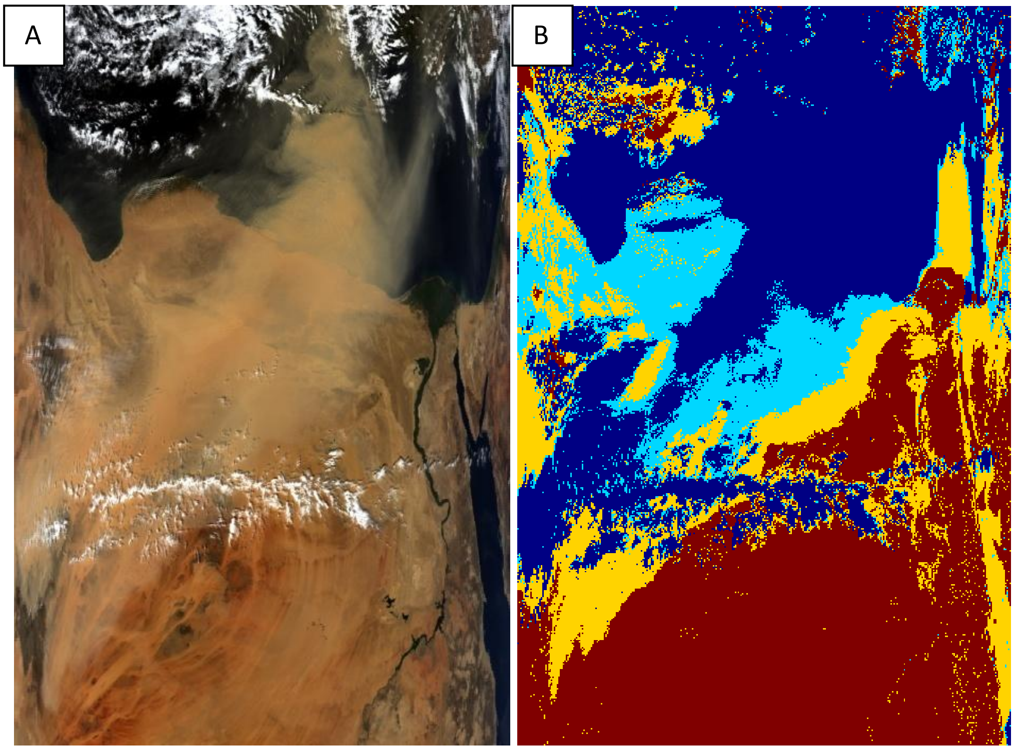

Figure 4 (A) is the true colour image was captured by Aqua over North Africa and (B) is the relative cloud mask on the right

The cloud mask algorithm uses a series of threshold tests applied to the 19 MODIS bands 1, 2, 4, 5, 6, 7, 17, 18, 19, 20, 22, 26, 27, 28, 29, 31, 32, 33, and 35 to identify the presence of clouds in the instrument field of view [22]. The cloud mask requires several ancillary data inputs: sun angle, azimuthal angle, viewing angle, land/water map at 1 km resolution and topographic elevation above mean sea level obtained from MOD03 (geolocation fields), and ecosystems global 1 km map of ecosystems based on the Olson classification system, and Daily NISE snow/ice map provided by NSIDC (National Snow and Ice Data Center), and daily sea ice concentration product from NOAA [22].

The cloud mask is not the final cloud product from MODIS; several Principal Investigators have responsibility to deliver algorithms for various additional cloud parameters, such as water phase and altitude. The specific tests executed are a function of surface type, Including land, water, snow/ice, desert, and coastal, and are different during the day and night [18]. The cloud mask outputs also includes results from particular cloud detection tests. Table 3 gives a description of MODIS cloud mask product (MOD35 and MOY35) bits.

Table 3 File specification for the 48-bits MODIS cloud mask [22]

BIT	DESCRIPTION KEY	RESULT
0	Cloud Mask Flag	0 = not determined 1 = determined
1-2	Unobstructed FOV Quality Flag	00 = cloudy 01 = uncertain clear 10 = probably clear 11 = confident clear
	PROCESSING PATH FLAGS	
3	Day/Night Flag	0=Night / 1= Day
4	Sun glint Flag	0 = Yes / 1 = No
5	Snow / Ice Background Flag	0 = Yes/ 1 = No
6-7	Land / Water Flag	00 = Water 01 = Coastal 10 = Desert 11 = Land
	ADDITIONAL INFORMATION	
8	Non-cloud obstruction Flag (heavy aerosol)	0 = Yes / 1 = No
9	Thin Cirrus Detected (near infrared)	0 = Yes / 1 = No
10	Shadow Found	0 = Yes / 1 = No
11	Thin Cirrus Detected (infrared)	0 = Yes / 1 = No
12	Spare (Cloud adjacency) (post launch)	(Post launch)

1km CLOUD FLAGS		
13	Cloud Flag - simple IR Threshold Test	0 = Yes / 1 = No
14	High Cloud Flag - CO2 Threshold Test	0 = Yes / 1 = No
15	High Cloud Flag - 6.7 µm Test	0 = Yes / 1 = No
16	High Cloud Flag - 1.38 µm Test	0 = Yes / 1 = No
17	High Cloud Flag - 3.9-12 µm Test	0 = Yes / 1 = No
18	Cloud Flag - IR Temperature Difference	0 = Yes / 1 = No
19	Cloud Flag - 3.9-11 µm Test	0 = Yes / 1 = No
20	Cloud Flag - Visible Reflectance Test	0 = Yes / 1 = No
21	Cloud Flag - Visible Ratio Test	0 = Yes / 1 = No
22	Clear-sky Restoral Test- NDVI in Coastal Areas	0 = Yes / 1 = No
23	Cloud Flag -7.3-11 µm Test	0 = Yes / 1 = No
ADDITIONAL TESTS		
24	Cloud Flag – Temporal Consistency	0 = Yes / 1 = No
25	Cloud Flag - Spatial Consistency	0 = Yes / 1 = No
26	Clear Sky Restoral test	0 = Yes / 1 = No
27	Cloud Test – Night Ocean Variability Test	0 = Yes / 1 = No
28	Suspended Dust Flag	0 = Yes / 1 = No
29-31	Spares	0 = Yes / 1 = No
250m CLOUD FLAG - VISIBLE TESTS		
32	Element(1,1)	0 = Yes / 1 = No
33	Element(1,2)	0 = Yes / 1 = No
34	Element(1,3)	0 = Yes / 1 = No
35	Element(1,4) 0 = Yes / 1 = No	0 = Yes / 1 = No
36	Element(2,1) 0 = Yes / 1 = No	0 = Yes / 1 = No
37	Element(2,2) 0 = Yes / 1 = No	0 = Yes / 1 = No
38	Element(2,3) 0 = Yes / 1 = No	0 = Yes / 1 = No
39	Element(2,4) 0 = Yes / 1 = No	0 = Yes / 1 = No
40	Element(3,1) 0 = Yes / 1 = No	0 = Yes / 1 = No
41	Element(3,2) 0 = Yes / 1 = No	0 = Yes / 1 = No
42	Element(3,3) 0 = Yes / 1 = No	0 = Yes / 1 = No
43	Element(3,4) 0 = Yes / 1 = No	0 = Yes / 1 = No
44	Element(4,1) 0 = Yes / 1 = No	0 = Yes / 1 = No
45	Element(4,2) 0 = Yes / 1 = No	0 = Yes / 1 = No
46	Element(4,3) 0 = Yes / 1 = No	0 = Yes / 1 = No
47	Element(4,4) 0 = Yes / 1 = No	0 = Yes / 1 = No

1.2.3. MODIS LAND PRODUCTS

- ***Surface Reflectance (****MOD09and MYD09****)***

The MODIS Surface-Reflectance Products (MOD 09) are estimates of the surface spectral reflectances for each MODIS Level 1B reflectance band 1, 2, 3, 4, 5, 6, and 7 assuming no atmospheric scattering or absorption. MOD09 consists of level 2G-Lite daily products MOD09GA and MOD09GQ, and level 3, 8-day composited products MOD09A1 and MOD09Q1, and daily level 3 CMG products MOD09CMG [23].

- ***Land Surface Temperature & Emissivity (****MOD11 and MYD11****)***

The MODIS Land Surface Temperature and Emissivity product MOD11 contains Level 2 and 3 LST and emissivity separately retrieved from Aqua and Terra MODIS data at spatial resolutions of 1 km and 5km over global land surfaces under clear-sky conditions. This product is used to retrieve LST for MODIS pixels with known emissivities in bands 31 and 32. The physics based day/night LST algorithm is used to simultaneously retrieve surface band emissivities and temperatures from a pair of daytime and night-time MODIS observations in bands 20, 22, 23, 29, and 31-33 over all types of land cover. The MOD11comb (combination) product contains Level 2 and 3 land-surface emissivities and temperatures retrieved through the combination of Aqua and Terra MODIS data. The MOD11comb surface temperature, with an enhanced diurnal feature, is more suitable for some applications than an Aqua or Terra product alone [6].

- ***Land Cover/Land Cover Change (****MOD12 and MYD12****)***

The MODIS global land cover product (MOD12) contains two scientific data sets (SDS): MOD12Q1 (global land cover), and MOD12Q2 (global land-cover dynamics). The MOD12Q1 SDS consists of five layers depicting different global land cover classifications. The MOD12Q2 SDS consists of seven layers that characterize seasonal time scale dynamics in ecosystems at global scale. MOD12Q1 and MOD12Q2 are both produced at a spatial resolution of 500m at annual and bi-annual time-steps respectively in collection5 [6].

- ***Gridded Vegetation Indices (****NDVI & EVI****) (****MOD13, and MYD13****)***

The MOD13 product consists of the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) with six global records at 250m, 1000m, 0.05m resolutions and at 16-day and monthly intervals) over land from each of the Terra and Aqua MODIS sensors. The VI products are made from the level 2 daily MODIS surface reflectance (MOD09) and complement each other in global vegetation studies [24, 25].

- ***Thermal Anomalies, Fires and Biomass Burning (****MOD14, and MYD14****)***

The MODIS Thermal Anomalies product MOD14 consists of various fire related parameters including: fire location occurring both day and night; the logical criteria used for the fire selection; and fire energy calculation. The product also contains 8-day-and-night fire occurrences, composite monthly day-and-night fire occurrences, gridded 10-km summary per fire class daily, 8-day and monthly, and a gridded 0.5° summary of fire counts per class daily, 8-day, and monthly [6].

- ***Leaf Area Index (LAI) and Fractional Photosynthetically Active Radiation (FPAR) (****MOD15 and MYD15****)***

MODIS FPAR is the Fraction of Absorbed Photosynthesis Active radiation that a plant canopy absorbs for growth in the 0.4 – 0.7nm spectral range. FPAR is the less unit fraction of the incoming radiation received by the land surface. MODIS LAI is the biomass corresponding to FPAR, and is also a dimensionless ratio (m^2/m^2) of leaf area covering a unit of ground area. Both of these variables are computed daily at 1km resolution from MODIS spectral reflectance for all vegetated land surface globally. MODIS LAI and FPAR products of Collection 5 include four products: Terra 8-day, Aqua 8-day, combined Terra and Aqua 8- and 4-day. The MOD15 FPAR and LAI are assumed as essential inputs for the MOD16 and MOD 17 data products [6, 26].

- ***Evapotranspiration (****MOD16 and MYD16****)***

MODIS evapotranspiration is a land surface product that represents all transpiration by vegetation and evaporation from canopy and soil surfaces. This product is generated in 1-dimensional vertical mm/day units and computed globally every day at 1km resolution; using MODIS land cover, and FPAR/LAI data and global surface meteorology. MODIS evapotranspiration uses water balance calculation, for hydrologic management, as a carbon cycle constraint, and for drought and fire danger mapping [6].

- ***Vegetation Production, Net Primary Productivity (****MOD17, MYD17****)***

The Vegetation Production, Net Primary Productivity product is generated using daily MODIS FPAR and LAI and global GMAO surface meteorology at 1km resolution for the global vegetated land surface. This product is used to compute the primary production of vegetation every day, and sums to net primary production (fundamentally vegetation growth). These variables provide the initial calculations for vegetation growing in season and the analysis of carbon cycle. They are also, used for estimating range of agriculture and forest production [6].

- ***Surface Reflectance BRDF and Albedo Parameter (****MOD43, MYD43****)***

Surface Reflectance is one of the key radiation parameters that are used for calculating the earth's energy balance. The MODIS reflectance product presents a substantial description of surface variation that is used to establish global land surface reflectance. The product requires multi-date clear sky, atmospherically corrected surface reflectance and The Bidirectional Reflectance Distribution Function (BRDF) model to create the surface variation and provide reflectance measures at a 500m resolution in seven spectral bands (1-7) and three broad bands (0.4µm - 0.7µm, 0.7µm - 3.0µm, and 0.4µm - 3.0µm). The generation of BRDF and reflectance requires collecting multiple looks at each pixel, so the BRDF and reflectance parameters are presented every 16 days with 1km spatial resolution in MODIS Level 3. A 32 day summary reflectance product at 0.25° spatial resolution is also presented. The surface anisotropy is also used to produce the nadir view angle corrected reflectance [6].

- ***Vegetation Cover Conversion (****MOD44, MYD44****)***

The Vegetation Cover Conversion MOD44 product is a database of land cover and change. Products are computed from 16-day composites of MODIS reflective and emissive bands. The MOD44B presents 250m sub-pixel estimates of the percentage of woody, herbaceous and bare cover along with leaf type and longevity. The MOD44A product, also at a 250m spatial resolution, presents a global warning of land cover change. This also includes the continual change due to deforestation via burning and inundation [6].

1.2.4. MODIS CRYOSPHERE PRODUCTS

- ***Snow Cover (****MOD 10****)***

The MODIS snow cover product includes six components: MOD10L2, MOD10L2G, MOD10A1, MOD10A2, MOD10C1 and MOD10C2. The MOD10_L2 Product is generated from calibrated radiance data (MOD02HKM), the geo-location product (MOD03), and the cloud mask product (MOD35_L2). Its output consists of snow cover SDS, a quality assurance (QA) SDS, latitude and longitude SDSs, local attributes and global attributes. The snow cover algorithm identifies snow-covered land; it also identifies snow-covered ice on inland water. The MOD10L2G Product is the result of mapping all the MOD10_L2 swaths acquired during a day to grid cells of a map projection. MOD10A1 level_3 daily snow product is the result of multiple mapping of the MOD10_L2G product. MOD10C1 is a daily global climate modelling grid (CMG) snow product providing a global view of snow cover at ¼ degree resolution and is mapped by processing the MOD10A1 product. MOD10A2 is an eight-day snow product and is generated from eight days of MOD10A1. The MOD10C2 product results from eight days of MOD10C1 product [27, 28].

- ***Sea Ice Cover (****MOD 29****)***

Sea Ice cover products are a set of products: MOD29 product is a level 2 5-Minute Swath at 1km resolution produced from the level 1 MODIS data product (MOD21KM), the geolocation product (MOD03), and cloud mask product (MOD35_L2). The product outputs are sea ice scientific data sets SDSs, ice surface temperature SDS, quality assurance (QA) SDSs, latitude and longitude SDSs, local attributes, and global attributes [29, 30]. MOD29P1D is a daily L3 Global 1km EASE-Grid Day; the product file consists of the same variables as MOD29 while MOD29P1N is a daily L3 Global 1km for the night time. MOD29E1D is a daily L3 global 4km [31].

1.2.5. MODIS OCEAN PRODUCTS

MODIS Ocean data products contain 36 Ocean Colour and 4 sea surface temperature (SST) science products. Level 2 Ocean products are grouped into 3 Ocean colour data types and one SST data type at 5 minute spatial resolution: ocean colour radiance products, ocean colour derived products group 1, ocean colour derived products group 2, and SST. Level 3 Ocean products are available in daily, 8 day, monthly and yearly averages, and at 4.63 km, 36 km and 1^o spatial resolutions. The following is a description of Level 2 Ocean products:

• **Ocean Colour Radiance Product** consist of 12 products: Normalized water leaving radiance at 0.41, 0.44, 0.48, 0.53, 0.55, 0.66 and 0.67µm, Aerosol optical thickness at 0.86µm, Epsilon of aerosol correction at 0.76 and 0.86µm, Aerosol model identification number (1,2), and Epsilon of clear water aerosol correction at 0.53 and 0.66µm.

• **Ocean Colour Derived Products Group 1** consist of 13 products: MODIS chlorophyll a concentration for Case 1 waters, two pigment concentrations (MODIS and CZCS), three chlorophyll fluorescence parameters, suspended solids concentration, three coccolithophore concentrations, a diffuse attenuation coefficient at 0.49µm, and phycourobilin and phycoerythrobilin absorptions.

• **Ocean Colour Derived Products Group 2** consist of 11 products: an additional chlorophyll- a concentration for Case 1 waters using the SeaWiFS algorithm, a semi analytic chlorophyll- a concentration for Case 2 waters, instantaneous photosynthetically available radiation (IPAR), absorbed radiation by phytoplankton (ARP), total absorptions (0.41, 0.44, 0.48, 0.53 and 0.55 µm), and chlorophyll and Gelbstoff absorption coefficients.

• **Sea Surface Temperature Product** consists of one thermal and one mid-infrared SST product. The former is produced from MODIS bands 31 – 32 (10.8–12.3 µm) whereas the latter uses the MODIS bands 22 – 23 (3.9 – 4.1 µm). Both are collected during day and night [11].

1.3 SOFTWARE SYSTEMS TO READ AND VIEW HDF FILES

MODIS data is not just one image file but is a set of image files and scientific data files that are saved in hierarchical data format (HDF) file type. Therefore, software systems are provided for reading and displaying the HDF files for different purpose and these are listed in the following subsections.

1.3.1. MODIS REPROJECTION TOOL

The MODIS reprojection tool (MRT) software is used to read and re-project between 14 projection types, convert files types to GeoTiff and Binary, sub-setting and sub-sampling with reprojection, sub-setting with format conversion and mosaicing with reprojection. This software only works with MODIS gridded products and can be used in GUI or command line modes. MRT will work on different of platforms: Linux, IRIX, Solaris and Windows. This software was developed by the Land Processes Distributed Active Archive Centre (LPDAAC) and can be downloaded from

https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool.

1.3.2. MODIS REPROJECTION TOOL SWATH

The MODIS reprojection tool Swath (MRTSwath**)** is used for reprojection from swath to 14 projection types, sub-setting with reprojection and format conversion with reprojection. MRTSwath only works with MODIS swath products and associated geolocation data products. MRTSwath can be used in both GUI and command line modes. This software was developed by LPDAAC and works on Linux, IRIX, Solaris and Windows platforms. It can be downloaded from

https://lpdaac.usgs.gov/lpdaac/tools/modis_reprojection_tool_swath.

1.3.3. HDF-EOS WEB-BASED SUB-SETTER

The HDF-EOS Web-based Sub-setter **(**HEW) can sub-set both swath and gridded MODIS products. HEW can be used in Web GUI and command-line modes, and works on Linux, IRIX, and Solaris platforms. HEW was devolved by the University of Alabama, Huntsville and can be downloaded from http://subset.itsc.uah.edu/hew2k/.

1.3.4. SPOT - SUBSETTABILITY CHECKER

SPOT checks if an HDF-EOS is sub-settable by HEW. It can only be used in command line mode and works on Linux, IRIX and Solaris platforms. The author is the University of Alabama, Huntsville and the tool can be downloaded from http://subset.itsc.uah.edu/hew2k/.

1.3.5. MODIS LDOPE TOOLS

These are 25 standard tools to assist the quality assessment of MODIS products. They are available only in command line mode and work on Linux, IRIX, Solaris and Windows platforms. The authors are LPDAAC and LDOPE and the tools can be downloaded from the URL

https://lpdaac.usgs.gov/lpdaac/tools/ldope_tools.

1.3.6. HDFLOOK

HDFLook is used for the visualization of HDF content for the following formats: Scientific Data Set; Vfiles; raster images.

It provides visualization of slices of data containing up to 6 indexes, display of file attributes, automatic detection of particular filling values (mask), displays data sets as ASCII pages of numbers, plots of transects and histograms on image planes, plots of SDS records, predictions of images and graphics PostScript prints, format conversions, and displays RGB images with optional map and grid overlays. HDFLook is available in GUI and batch modes, and works on Linux, IRIX, Solaris, Windows, Mac, DEC, HP and IBM-AIX platforms. The authors are L. Gonzalez and C. Deroo, Université des Sciences et Technologies de Lille. The software can be downloaded from the URL

http://www-loa.univ-lille1.fr/Hdflook/hdflook_gb.html.

1.3.7. HDF-EOS TO GEOTIFF CONVERTER

This HDF-EOS to GeoTiff Converter (HEG) software is used for format conversion to GeoTiff, binary and or HDF-EOS grids, parameter and spatial sub-setting and data sub-sampling. It can be used in both GUI and command-line modes and works on Linux, IRIX, Solaris, Windows and Mac platforms. HEG was developed by ECS Project Office and can be downloaded from the URL

http://newsroom.gsfc.nasa.gov/sdptoolkit/HEG/HEGHome.html.

1.3.8. HREPACK

This HDF internal compression and decompression and or chunking tool can only be used in command line mode. The compression formats available are RLE, Huffman, gzip, JPEG, and szip and it works on AIX, AMD Opteron, FreeBSD, HP-UX, IA, IRIX64, Linux, Mac, Solaris, Cray and Windows platforms. The authors are NCSA, University of Illinois and the tool can be downloaded from the URL

http://hdf.ncsa.uiuc.edu/hdf4.html.

1.3.9. MATLAB

Matlab is widely used in research, because it includes an enormous number of tools, has a flexible easy to use user interface and has a useful help library. Matlab provides GUI and command line interfaces to browse and read HDF files. In this study Matlab provides the platform used for the detection of dust storms.

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