Mapping China Using MODIS Data: Methods, Software and Products

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Abstract: This paper presents a software system, MODISoff, which can process MODIS IB data automatically to generate various products covering the whole China. Some new algorithms were proposed to overcome the shortcomings of NASA MODIS standard products. The strength of the LAI retrieval method is that it avoids using two incompatible methods in NASA LAI product. The algorithm for estimating both land surface reflectance and aerosol optical depth is based on multi-temporal observations and produces more accurate products. The cloud mask algorithm detects low clouds better. Some of key inputs for these algorithms are localized over China. This system also produces some new products that are not available in the standard NASA product suite, including the forest burned scar and PAR. The data processing system is operationally run in the National Scientific Data Center for Resources and Environment, Chinese Academy of Sciences.

Key words: MODIS; data processing system; remote sensing

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1. INTRODUCTION

Global environmental change is the main issue facing humans today. Understanding our living environment is increasingly dependent on global, integrated, and quantitative descriptions of our Earth system. Different methods are used to gather data from different areas and serve for many different applications. Satellite data are some of the most important and voluminous sources of information available for terrestrial research. This is especially true since NASA launched its Earth Science Enterprise in 1991 and proceeded to develop the Earth Observing System (EOS), providing a comprehensive method to exploit the interaction of atmosphere, ocean, land and life. As a part of EOS, two Moderate Resolution Imaging Spectroradiometer (MODIS) sensors on-board TERRA and AQUA satellites were launched on December 18, 1999 and May 4, 2002 respectively. With 36 spectral bands, MODIS covers the electromagnetic spectrum from 0.4 to 14.4 μm with a spatial resolution from 250m to 1km and a temporal resolution as frequent as two days. MODIS data are the most comprehensive remote sensing data available to date. MODIS can simultaneously capture the information from the ocean, land, and atmosphere. NASA’s MODIS science team, including land, atmosphere, ocean, and calibration experts, designed 44 standard products. Most of these standard products currently can be downloaded from NASA data centers. Although great efforts were made to develop the global satellite product algorithms, most all MODIS standard products need further improvements. Five examples are: (1) The spatial resolution of some products are too coarse to be applied locally, such as its 10km ×10km aerosol
products that are not suitable for regional pollution monitoring; (2) Some important products are not included, such as fire burned scar and PAR; (3) Many algorithms are obsolete, such as the dark object method for removing the effects of aerosols was designed in 1988; (4) Most algorithms are based on single scene data resulting in low accuracy; (5) The global input parameters are not consistently suitable for the Chinese environment, such as global land cover and LAI products.

To utilize the MODIS data efficiently, we have developed the software MODISoft that can process automatically voluminous MODIS multi-temporal data to produce various high-level biogeochemical products. The original MODISoft was developed in July 2002 and released the first version in December 2002. The system has been run operationally by the Chinese National Agency of Forestry for fire monitoring and in the National Scientific Data Center for Resources and Environment, Chinese Academy of Sciences for data generation. In this paper, we describe the software and some products that are generated by this system.

2 SYSTEM OVERVIEW

MODISoft is a fully integrated, automatic and scalable system for MODIS data processing. It currently comprises four modules for basic operations, atmospheric product and land product generation, and hazard monitoring. It can produce high-level products from MODIS IB data, georeference and composite them to remove cloud and noise effects. The system framework is shown in Fig. 1. The MODISoft is developed by C code and can be run independently without the support of other additional third-party software. The C code programming makes the system more efficient in processing huge volumes of MODIS data. The modular structure of the system enables it to be easily updated to support new sensors and add new functions in the future. Meanwhile, such a structure also makes it easy to expand some new modules. A graphical user-friendly interface (GUI) has been designed to assist the operations of data input, display, product generation, and output. The console command also is provided to allow the user to process the data in batch, which is especially useful for processing the huge amount of data that need to run for long periods of time. The accessory databases are required to serve as inputs and are prepared for the system in advance. The users do not need to know which accessories are needed when they generate products.

The basic module includes MODIS IB data input, preprocessing, georeferencing, display, image enhancement, image display, property adjustment and data output. To exchange data easily with other remote sensing software, the generated product can be created in HDF, geotiff and flat raster binary image files. The HDF format can be scaled to 8, 16 or 32 integer bits according to the data type, and the scale property can be added. The geotiff format includes float, color, and gray types. The atmospheric module focuses on generation of atmospheric products from MODIS IB data. The products include cloud mask, aerosol optical depth, and precipitable water amount. The land module can generate land surface reflectance, land surface temperature/emissivities, vegetation index (NDVI/EVI), leaf area index, and land cover classification. The hazard monitoring module extracts the hazard information, and can be extended to be an independent operational monitoring system. This module currently can detect drought, fire, dust storm and snow events.

3 THE PROVED AND NEW PRODUCTS FROM MODIS

NASA MODIS standard products include aerosol
(MOD04), cloud mask (MOD35), land surface reflectance (MOD09), land surface temperature (LST, MOD11), land cover classification (LCC, MOD12), vegetation indices (VI, MOD13), thermal anomalies (MOD14) and burned scar (MOD40), leaf area index (LAI, MOD15), MODIS surface resistance and Evapotranspiration (ET, MOD16), vegetation production and Net Primary Production (NPP, MOD17), surface reflectance BRDF/Albedo parameter (MOD43), vegetation cover conversion & vegetation continuous fields (MOD44). All these standard products can be downloaded from NASA web site free of charge except MOD16. MODISsoft™ can generate all these products, and the algorithms for aerosol, cloud mask, and land surface reflectance are improved. Photosynthetically Active Radiation (PAR) and fire burned scar products are designed and available for the first time for MODIS data. In this section, the improved and new products will be introduced.

3.1 Aerosol products

Aerosols are important components of the Earth-atmosphere system that strongly affect climate systems, plant photosynthesis, and hydrologic cycle by scattering and absorbing the incoming radiation from the Sun, modifying the magnitude and directionality of the downwelling radiation, and simultaneously, cloud formation and albedo. Epidemiological studies have also shown that small particles in the air, when inhaled, can penetrate into the lung and cause many adverse health effects. Aerosols, especially dust, are a key contribution to the transportation of nutrients elements to forest and ocean ecosystem, and mitigate the function of acid rain. Satellite remote sensing is uniquely able to routinely measure aerosols over vast areas. Retrieval of aerosol properties over the ocean from many different satellites have been successful, but it is still a challenge over land due to variation of land surface reflectance. The aerosol retrieval method can be concluded as:

(1) The dark object based method was proposed by Kaufman and Sendra, which assumes that the dark land surface contributes little to the satellite signals and the short wavelength reflectance can be estimated from mid-infrared reflectance that are rarely contaminated by aerosols. There are several advantages for this method. First, the aerosol retrieval uncertainties from the surface reflectance are smaller for low surface reflectance because their contributions to the sensor observations are small. Second, the absorption effect of aerosols is small for low surface reflectance. However, there are also several disadvantages for this method. First, it cannot be used over bright land surfaces although it has been extended to those surfaces with band 7 reflectance less than 0.4, and the uncertainty of red band is large. Third, the dark object method is not suitable for thick aerosols.

(2) The cluster-based aerosol method assumes that those surfaces with similar mid-infrared reflectance have similar shortwave reflectance, and the reflectance of hazy pixels can be inferred from those clear-sky pixels with similar shortwave reflectance. This method can estimate the reflectance of bright surfaces but it cannot be used to MODIS data because of the BRDF effects from the large swath of MODIS interfer.

(3) The composite background reflectance method assumes that surface reflectance is stable during a certain period of time and can be estimated from the cleanest pixels of multitemporal observations. This method has potential for successful aerosol retrieval. However, the compositing interval and pixel selection criterion are difficult to determine. And, the shadow and BRDF effects removal are also difficult tasks.

The methods proposed do not resolve these problems well, so the improvement is required to build an operational system. In MODISsoft™, a more powerful aerosol retrieval algorithm has been proposed and implemented to process large volumes of data automatically. The assumption is that there is high correlation between MODIS band 1 and 3 in land surface, but their ratio is variable for observational angles and vegetation coverage. Therefore, we build a ratio database for different geometric conditions and vegetation coverage. Depending on this database, the observational
reflectances and model reflectances best matching method is used to retrieve aerosol from bands 1 and 3 simultaneously. Fig 2 is an example for processing a single granule data.

![Aerosol retrieval result](image)

**Legend**

0 1.0 2.53.0

Fig. 2. Aerosol retrieval result (Date: 2000-245-0350)

The left image is a band 1, 4, 3 composite image and the right is the retrieved aerosol optical depth.

3.2 Land surface reflectance

Land surface reflectance, which represents the ratio of reflected radiation to incoming solar radiation at the Earth’s surface, is an important parameter in describing the radiative properties of the Earth’s surface. The MODIS Land surface reflectance product (MOD09) is an estimate of the surface spectral reflectance for each band, as it would have been measured at ground level if there were no atmospheric scattering or absorption. The MOD09 product is computed from the MODIS Level 1B land bands 1, 2, 3, 4, 5, 6 and 7 (centered at 648nm, 858nm, 470nm, 555nm, 1240nm, 1640nm, and 2130nm, respectively). The correction scheme includes corrections for the effect of atmospheric gases, aerosols, and thin cirrus clouds; the correction algorithm is applied to all non-cloudy pixels. Because the MODIS aerosol algorithm is based on the dark-object assumption, which can not work on bright surface or high aerosol thickness, the current land surface reflectance is not corrected for the aerosol effect in bright regions. We designed a new algorithm to separate aerosol and land surface reflectance. This algorithm assumes that the band ratio of band 1, 3 is constant for certain vegetation cover and this ratio can be estimated from statistics of large amount of clear sky data. The best matching method was used to determine the observational ratio and background ratio. It can be applied to any land surface to correct high thickness aerosol. The corrections of gas absorption, water vapor and cirrus are as same as NASA method, which was performed before aerosol removal. Then the aerosol and land surface reflectances were decoupled. Fig 3 is the result. These figures show that atmospheric correction has removed the haze.

3.3 Cloud mask

Cloud mask is a key step for remote sensing data processing. For example, selection of the candidate pixels for land surface reflectance composite requires cloud mask information. Also, the presence of clouds seriously affects the accuracy of aerosol data. Mis-classification of cloud as aerosol will lead to overestimation of aerosols, but identification of high aerosols as cloud will seriously underestimate aerosol distribution. Ackerman et al. proposed a comprehensive MODIS cloud mask algorithm, that uses 17 of the 36 MODIS bands to detect different cloud types.

![Before and after atmospheric correction](image)
Martins et al. improved the cloud mask over oceans using a spatial variant technique\textsuperscript{[14]}. However, low clouds, especially those located in forests and valleys, usually cannot be detected. This shortcoming leads to many uncertainties for those applications depending on clouds to flag land surface reflectance retrieval, composite, and aerosol retrieval. We find that MOD\textsuperscript{IS} bands 3 and band 9 are very sensitive to clouds. But the MOD\textsuperscript{IS} cloud detection algorithm does not use these bands. In MOD\textsuperscript{IS}oft\textsuperscript{a}, the cloud mask and aerosol retrieval are simultaneously performed. Band 3 pixels with reflectances greater than 0.3 are flagged as cloud or dust, and dust is differentiated from bright temperature difference of band 31 and 32. The aerosol was retrieved for the rest of pixels. If the aerosol thickness is less than 0.5, the pixel is flagged as clear. For those pixels with thickness more than 0.5, if B T31—B T32 is less than 0, they are flagged as aerosol. If the ratio of R0.87 and R0.66 is between 0.9 and 1.1, they are flagged as cloud; otherwise they are flagged as uncertain. Fig. 4 illustrates the result of this procedure. The NASA algorithm eliminates the low cloud located over the valley in the center panel of Fig. 4, but the new algorithm is capable of eliminating them more effectively (right panel).

![Fig. 4 Cloud mask comparison (Data date: 2005176 0345)](image)

3.4 New composite method

The influence of clouds, shadow and aerosol contamination are problems for measurements of land surface reflectance from satellite remote sensing technology. These limitations can be substantially mitigated by frequent observations, which increase the likelihood of obtaining a clear-sky view of the surface. Compositing procedures are therefore required to create most approximate land surface reflectance datasets from those observations when the surface conditions can be considered static during the period\textsuperscript{[51]}. Multiobservations data compositing is a procedure in which co-registered data acquired during a given period are combined, and the spectral values of the date presenting the best conditions under given criteria are selected to construct the resulting image. Various composite approaches, such as maximum bright temperature, maximum visible band, maximum vegetation index, or some combination of these have been proposed to fulfill different objectives to minimize the clouds, shadow and aerosol contamination\textsuperscript{[16]}. The two most common methods are selection data with the maximum NDVI (MaxNDVI) and the minimum shortwave band reflectance (MinBand). MaxNDVI is supposed to minimize cloud cover, enhance the vegetation signal, and avoid large view angle data\textsuperscript{[55]}. However, it has been shown that it can actually result in selection of off-nadir data\textsuperscript{[77]} and cloud retention over non-vegetated surfaces. The MinBand and method was proposed to avoid some of the problems found with MaxNDVI and has been applied to produce Earth surface reflectivity product for various sensors data. Because clouds and aerosol effects could increase the visible band reflectance over land, selection of lowest value data raises the likelihood of choosing the clear-sky pixels.
However, this approach is apt to select shadow pixels that have lower reflectance. Although some shadows can be detected before compositing procedure, it is still a challenge to avoid the shadow effect. In MODISOff, a new method to remove cloud shadow was introduced. We assume that the pixel with minimum apparent reflectance ratio from band 3 and band 7 can be identified as a very clear pixel over land under clear-sky conditions. This assumption is based on the fact that aerosols and off-nadir effects increase greatly the reflectance in band 3 but have little effect on band 7. Therefore, our algorithm will select the pixel with the least aerosol contamination and the ones that are the closest to nadir. Because band 3 has more diffused radiation than band 7 in shadow, the ratios of band 3/7 in shadow will higher than the non-shadow. Fig. 5 illustrates the composite results.

![Minimum blue composite and MODISOff composite results](image)

Fig. 5 Minimum blue method and MODISOff composite results

3.5 Leaf area index and fraction of photosynthetically active radiation (FPAR)

LAI and FPAR are biophysical variables that describe canopy structure and are related to functional process rates of energy and mass exchange. Both LAI and FPAR are used extensively as satellite-derived parameters for calculation of surface photosynthesis, evapotranspiration, and NPP. These products are essential in calculating terrestrial energy, carbon, water-cycle processes, and the biogeochemistry of vegetation. The LAI product is an input in biogeochemical models to produce conversion-efficiency coefficients, that are combined with the FPAR product to produce daily terrestrial photosynthesis and annual NPP.

Estimation of LAI from satellite data is challenging. A simple method is to establish a regression relationships with a vegetation index such as NDVI, but the relationships with NDVI vary with land cover so the application is restricted to a local region. The NASA product used a physical radiative transfer model to inverse LAI and FPAR, but their products are larger than measurement values in nearly all regions. We embedded the BRDF-based method developed by Chen et al. in MODISOff. The land cover map used NLCC land cover data which are more accurate in Chinese environment. The validation of this map in four forest site distributed in different regions of China have errors of ±1 (Fig. 6).

3.6 Photosynthetically active radiation (PAR)

Photosynthesis is the core process for matter and energy exchange between the land and atmosphere. Photosynthetically active radiation (PAR), as the key part of photosynthesis process controlling the vegetation production, usually is required as an input for modeling photosynthesis from single plant leaves to complex plant communities. Usually, PAR is estimated from global radiation observed by meteorological stations and then interpolated to cover a large area. However, only a few routinely operational meteorological stations measure global radiation, which is not enough for spatial interpolation. Sometimes, the global radiation for missing stations can also be estimated with models from other observed parameters such as temperature and precipitation. This indirect estimation almost certainly contains large errors. Estimation of PAR from remote sensing data has become the preferred choice. Frouin and Pinker reviewed the methods for estimating incident PAR from...
ISCCP (International Satellite Cloud Climatology Project) and TOMS (Total Ozone Mapping Spectrometer) observations\textsuperscript{[21]}.
Dye and Shibasaki compared different PAR products from ISCCP-BR, ISCCP-IL, and TOMS PAR with ground data, and found the RMS differences are 28.1\%, 13.7\% and 7.2\% respectively\textsuperscript{[22]}. Currently, high-resolution PAR data over land surfaces is unavailable. The MODIS team has to disaggregate the NASA DAO (Data Assimilation Office) assimilated PAR product of 3-hourly 2° by 2.5° spatial resolution to drive the BDM\textsubscript{E}-BGC model to generate 1km NPP and PSN (net photosynthesis) products\textsuperscript{[23]}. Therefore, the coarse PAR data will continue to be insufficient for regional applications for some time.

Solar radiation of the Earth’s surface is mainly determined by atmospheric conditions. If atmospheric components such as ozone, vapor, aerosol and cloud then PAR can be estimated simply by a radiative transfer model. However, satellite observations are a mixture of atmosphere and Earth surface signals, from which the atmospheric parameters and the land surface reflectance must be decoupled. Several atmospheric products were developed by the MODIS scientist team that can be downloaded freely from NASA DAAC, that can estimate PAR over land by a simple algorithm\textsuperscript{[24]}. But these MODIS products, that are retrieved mainly from single scene data, contain many uncertainties. For example, the MODIS aerosol products are unavailable over bright land surfaces or when heavy aerosols occur\textsuperscript{[11]}. In such circumstances, PAR is overestimated. To retrieve aerosols over these surfaces, multi-temporal data methods have been developed, that use the minimum visible band data to represent the land surface reflectance with no atmospheric contamination. For example, Gu et al estimated PAR from GOES data\textsuperscript{[25]} and Liang et al estimated PAR directly from the multi-temporal MODIS top-of-atmosphere (TOA) radiances, which can reduce uncertainties from atmospheric model selection\textsuperscript{[26]}. The Liang et al method has been validated by ground data from sites in the USA, which showed that the results are reasonably accurate. However, several shortcomings exist in current multi-temporal composite based methods. First, it is difficult to determine the length of composite periods. If periods are too long, the land surface changes substantially. But if periods are too short, cloud effects may be serious. Second, shadow may contaminate the composite results, and seasonal haze may always exist in some regions which makes it impossible to find a clear-sky pixel in the composite period.

We propose an operational algorithm in MODIS of\textsuperscript{2} that produces PAR from MODIS satellite observation-
al radiance (MOD02/MYD02) over China. Based on the method proposed by Liang et al., the new method directly estimates the instantaneous PAR from satellite observational radiances, so the errors of the atmospheric model can be minimized[26]. However, the land surface reflectance are from MODIS 8-day composite land surface (MOD09/MYD09) and 16-days BRDF (MOD43B1/MCD43B1) products, which is different than Liang et al method from the time series interpolation of annual smallest blue band data. Our method first generates the normalized land surface reflectance from BRDF-corrected MODIS MOD09/MYD09 by MOD43/MCD43 products, and the cloudy or noise pixels are removed by time-series interpolation. Then, normalized land surface reflectances are converted to the land surface reflectance with the same geometric angle as the MODIS MOD02/MYD02 data. Finally, these two kinds of information are used to retrieve the instantaneous and daily PAR. There are several improvements in this method: (1) the dark-object based atmospheric correction have been performed before compositing, so many aerosol effects can be removed from the MOD09/MYD09 data; (2) the cloud and shadow pixels are flagged before compositing; (3) the 8-days composite is long enough to capture many land surface changes; (4) the BRDF effect can be corrected by MOD43/MCD43 products; (5) the cloud and noise pixels in the composite data can be removed by time-series interpolation. Fig. 7 is the instantaneous PAR results in GMT 03: 20, Julian day of 2005.

4 FUTURE WORK

In the current version, many functions in MODISoft are not integrated into a user-friendly GUI system. Some sub-systems are designed to be more convenient for use, and some modules can be used only in our lab environment. We intend in the future to integrate all subsystems in the same operational style.

We intend to update the MODISoft system as soon as the new or improved algorithms become available. We are trying to design new algorithms for MODIS data processing, such as LST and emissivities separation algorithms, and a new albedo algorithm that can process a single observation. The new automatically operational monitoring subsystem will include other applications, such as a forest change monitoring system, dust storm monitoring system and aerosol air pollution system. Some algorithms designed for processing MODIS data can be easily applied to other satellite data. With its module-based program structure, MODISoft will be developed for an automatically quantitative remote sensing data processing platform.

REFERENCES


