OPERATIONAL AEROSOL OPTICAL MAPPING FROM REMOTELY-SENSED DATA OVER LAND SURFACE IN CHINA

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ABSTRACT:

The atmosphere contains solid and liquid particles (aerosols) and clouds, which interact with the incoming and outgoing radiation in a complex and spatially very variable manner. Aerosol particles are a largely natural, though highly variable, component of our atmosphere. Aerosols affect our environment at the local, regional, and global levels. There are many factors that are known to influence climate, both natural and human-induced. The increase in concentrations of greenhouse gases and aerosols through human activity is of particular concern. The effect of the increasing amount of aerosols on the radiative forcing is not yet well known. Regional patterns of climate change depend significantly on the time dependence of the forcing, the spatial distribution of aerosol concentrations and details of the modelled climate processes. Determination of aerosol optical depth from satellite remote sensing measurements is extremely complex due to the large variability of aerosol optical properties. Significant simplification occurs when measurements are taken over water since the ocean reflection signal can be taken as negligible in the near infrared. Unfortunately, over land, most of the signal can be attributed to ground reflectance. In this paper we propose a new approach to retrieve aerosol properties over land surfaces, especially high reflectance surface including arid, semiarid, and urban areas, where the surface reflectance is usually very bright in the red part of visible spectrum and in the near infrared, but is much darker in the blue spectral region. The quantitative retrieval of aerosol optical thickness from satellite data for land surface has been successfully conducted in China using MODIS and AATSR data. The results agreed with AERONET in situ measurement very well with averaged relative error less than 10%. The algorithm developed makes full use of the high frequency multi-temporal information and multi-spectral information from MODIS and AATSR, without any a prior knowledge of the underlying land surface characteristics. Fused with the national aerosol measurement network data, the national AOT map can be produced at 5km spatial resolution on the daily base. This national climate aerosol optical thickness data will be useful for the research of regional response to the global climate change.

1. INTRODUCTION

Atmospheric aerosols influence climate in two main ways, referred to as direct forcing and indirect forcing. In the direct forcing mechanism, aerosols reflect sunlight back to space, thus cooling the planet. Sooty aerosols from such processes as biomass burning absorb some of this solar energy, leading to a local atmospheric heating which may alter stability and convection patterns. The indirect effect involves aerosol particles acting as (additional) cloud condensation nuclei, spreading the cloud's liquid water over more, smaller, droplets. This makes clouds more reflective, and longer lasting.

It is very important that we are able to build up a complete picture of aerosols across the globe, so that we may understand how they vary in both time and space. It is even more important, however, that such observations be on-going, so we may monitor any build-ups which may be occurring. After all, since our present climate is a reflection of our current atmosphere - including its greenhouse gases and aerosols - it is the changes in these components which will lead to climate change. Before the satellite era, information on aerosols came from limited surface based observations, which are not sufficient to describe their spatial and temporal variability of aerosols (Levy and Pinker 2006).The only way to achieve an on-going global coverage is by satellite observation.

Aerosol could be sampled remotely, from satellite, but only indirectly, by means of a combination of various wavelengths of upwelling radiation (Rosenfeld and Lensky, 1998). Even then numerous assumptions are required. For years, many algorithms have been applied to these satellite datasets to retrieving information useful for studying aerosol over land (Kokhanovsky et al., 2007).

Satellite observations of reflected and emitted radiances are increasingly being used to monitor aerosols and their interactions within the climate system (King and Kaufman, 2000). A highly successful project is the NASA's Moderate Imaging Spectrometer (MODIS) (Salomonson et al., 1989), which has been observing from aboard the Terra (since 2000) and Aqua (since 2002) satellite platforms. Current state of the art space borne imagingradiometers like the Moderate Resolution Imaging Spectro-Radiometer (MODIS) or the Multi-angle Imaging Spectro-Radiometer (MISR) offer great possibilities for aerosol remote sensing. Aerosol optical depths and particle properties are independently retrieved from these radiances using methodologies and algorithms that make use of the instruments' corresponding designs.

The retrieval of AOD over land is more demanding because the surface reflectance is generally not only higher, so it provides

less sensitivity to changes in aerosols, but varies spatially and temporally. There is an even higher demand on information about aerosol over land because most aerosol emission sources, natural and anthropogenic, are on land. Additionally, knowledge of the Bidirectional Reflectance Distribution Function (BRDF), which describes the angular reflectance properties, is required. Inaccuracies of 0.01 of the surface reflectance can result in AOD variations1 of 0.1 (Hauser *et al.* 2004).

The retrieval of the aerosol optical thickness over land remains difficult because of the complexity of the Earth land surface. The surface reflectance of land surface is usually unknown and varies with wavelength. Several algorithms have been applied to satellite datasets to solve the inverse problem of separating the surface and atmospheric scattering contributions. For instance, MODIS retrievals of aerosol over land (Kaufman et al., 1997; Remer et al., 2005) are based on the correlation of reflectances in the visible and shortwave infrared (SWIR). Dark, dense vegetation has a very low reflectance in the blue and red wavelength regions and the surface reflectance at wavelengths in the visible are proportional to those in the mid-infrared (Hansen et al, 1990). This has allowed the development of algorithms to retrieve Aerosol Optical Depth (AOD) over dark vegetation (called dark targets) (Kaufman et al, 1985, 1996, 1997). Dark pixel method has been proposed among researchers to retrieve aerosol properties over dark pixels, such as water bodies and vegetation areas (Liu, et. al, 1996).

Another possibility is to use multi-angle observations of the same ground scene, as is done with MISR and AATSR (Diner et al., 2005; Grey et al., 2006a,b; North et al., 1999, 2002; Thomas et al., 2005). This makes it possible to accurately account for directional surface scattering in the retrieval procedure. Some studies use polarized light for aerosol retrieval, e.g., from POLDER, employing the fact that atmospheric scattering is much more polarized than surface reflection (Deuze et al., 2001). The BAERMERIS algorithm (von Hoyningen-Huene et al., 2003) is based on studies of TOA reflectances in the blue region, where most surface types are only weakly reflective and the scattering from the atmosphere contributes more to the observed signal. The MISR Level 2 aerosol product reports regional mean aerosol optical depths at 17.6 km×17.6 km resolution over the 380 km swath of each MISR orbit (Martonchik et al., 2002). The MODIS aerosol retrievals are performed using two separate algorithms, one for aerosols over land and the other for retrievals over ocean [Remer et al., 2004].

However, these diverse algorithms and approaches do not always give consistent values of the aerosol properties for a given ground scene. The problem is further complicated by the fact that the information content of satellite measurements is underconstrained as far as aerosol measurements are concerned. It is not always possible to constrain the phase function and the single scattering albedo from measurements themselves. Therefore, a priori assumptions are used that are typically based on prescribed aerosol models. Depending on the aerosol properties employed, and on the performance of the algorithms and accuracy of the underlying assumptions, different values of aerosol optical thickness may be retrieved.

This paper is concerned with operational Aerosol Optical Thickness (AOT) retrieval for China mainland. We propose this new high performance aerosol retrieval algorithm that is used for Moderate Resolution Imaging Spectroradiometer (MODIS)

from Earth Observing System (EOS) satellite data. A methodology using multi-resource remotely sensed data and available aerosol retrieval algorithms in an operational scheme is demonstrated. The algorithm comprises two complementary parts, collectively used in a distributed application (Xue *et al.* 2008). The first part is the modified multi-angle AOT retrieval algorithm described in our previous research publications (Tang et al., 2005), which is used for retrieval over land for a given region. This is a more general technique compared to DDV method that is based on the NASA near IR-visible surface albedo correlation approach and therefore restrictedly depends on the surface type (dense dark vegetation, or heterogeneous land) (Kaufman *et al.*, 1997). The ground station data are routinely coming from more than 16 nationwide locations by the AERosol Robotic NETwork (AERONET) of ground-based sun- and sky-scanning radiometers(Smirnov *et al.*, 2000) are used for assimilation as variables describing model initial states. The remainder of the paper is structured as follows. Section 2 describes the methodology of AOT retrieval. Section 3 describes the design of algorithms used to deal with task partition, and a detailed description of DPPA algorithm for load-balanced parallelization. Section 4 introduces the implementation for high performance algorithms. Section 5 first describes the test-bed and data used in this study, and then presents the experimental results. Finally, Section 6 concludes with some remarks.

2. AEROSOL PROPERTY RETRIEVAL OF MODIS DATA

In this section, we provide algorithmic description of retrieval for AOT of remotely sensed image scenes.

2.1 Model

Our retrieval strategy is based on a few assumptions and other considerations:

1. Atmospheric aerosols are homogeneous within a 10 km^2 region at the surface, growing to about 75 km in area at an altitude of 10 km. With this assumption, the different effective path lengths, observed through the atmosphere, vary in a predictable way.

2. Cloud-contaminated sub-regions are filtered out.

3. Between two pass observations at very short interval, the ground surface bidirectional reflectance properties do not change. And between two pass observations at very short interval, aerosol types and properties do not change.
Relation between the ground surface reflectance A and apparent reflectance (reflectance on the top of atmosphere) A' is used, which was proposed by Xue and Cracknell (1995) as follows:

$$A = \frac{(A'b - a) + a(1 - A')e^{(a-b)\varepsilon\tau_0^\lambda \sec\theta'}}{(A'b - a) + b(1 - A')e^{(a-b)\varepsilon\tau_0^\lambda \sec\theta'}} \tag{1}$$

where a=sec θ , b=2, ε is backscattering coefficient, usually set at 0.1. The solar zenith angle is calculated from latitude, longitude, and satellite pass time or the data set for MODIS. The atmospheric optical thickness τ_0^λ is determined by the atmospheric turbidity state at passing time. The core model is pure numerical code of quasi Means of Newton iteration to

derive parameters by solving simplified radiative transfer equations above. The model uses 14 Terra and Aqua spectral bands as inputs, and is carried out on pixels.

2.2 Ground-station data assimilation

The objective of data assimilation is to improve the initial state of the model by combining information from various sources such as ground-station based observations in space and time of the variables of interest. Within a data assimilation framework, we chose Angstrom's turbidity coefficient β and wavelength exponent α as driving variables, which force the system. Reflectance A and A' is state variables that provide a complete description of system behavior. The model characterizes the relationships between driving variables and state variables. AOT are output variables, which are observable functions of the state variables.

To derive the state variable at model time step, interpolation technique, such as inverse linear powered interpolation, is used to interpolate the dispersed ground station observation points onto geographic grid with regular 1 longitude/latitude degree interval in a geographic projection. The ground station data are routinely come from more than 16 nationwide locations by the AERONET of ground-based sun- and sky-scanning radiometers. Then ground data and satellite data are matched by geo-reference. With a 'calibration' method, model parameters/initial states are adjusted to obtain an optimal agreement between the retrieved and the observed state variables. The sensitive and uncertain initial parameters are calibrated either manually or automatically by running the model with various combinations of parameter values within realistic ranges.

2.3 Algorithm description

The algorithm determines that any of the 1×1 pixel sub regions (defined as 1 km $\times$ 1 km in size) can be classified as heterogeneous land, and the execution defaults to the synergy model. As shown in Figure 1, a step-by-step approach of the retrieval workflow is described below.

1. The model starts with the setting up of geometric and processing parameters. Geometric parameters supply the longitude, latitude, sun and view zenith angles as well as azimuth angles. Processing parameters provide information about the atmospheric data, cloud mask, and AERONET ground-based data.

2. The next process of radiative calibration is applied, where the model converts instrument counts to top of the atmosphere reflectance.

3. Effects of spectral absorptions of water vapour, CO_2 and O_3 are fixed. The clouds and sun glint pixels are masked using the MODIS clear sky discriminating method.

4. AOT retrieval is an operational scheme comprises of ground station data assimilation and the synergy model.

5. After geometric correction and map projection, the step of mosaic is applied to stitch individual images in a larger composite, and remap the granules onto a latitude and longitude grid covering the China land.

6. The last step is finalizing the AOT product to permanent storage. When information of geophysical phenomena needs to be stored, the Hierarchical Data Format (HDF) format is used.

3. AOT RETRIEVAL OVER CHINA MAINLAND

3.1 Data and test-bed

The image scenes used for experiments were collected by MODIS instrument, which covered China land. Each mosaic (geographic projection ,range 15° N -55° N, 70° E-135° E , spatial resolution 0.01° , data array 6501x4001) was selected from AQUA/TERRA database of daytime images, which consisted of 14 granules, 7 spectral bands and a total size of approximately 6.7 Gbytes. The data were acquired from the NASA Distributed Active Archive Centre. Volume of auxiliary data, e.g. the AERONET data, atmospheric data, and cloud masks (MODIS L35) are about 1.2 Gbytes.

We installed the application in a test-bed of computational Grid pool in the IRSA, CAS. We configure levels of the Grid. Level 1 is connected to the dedicated CPU server serving as database and invokes tasks directly without parallelization. Level 2 and Level 3 reside on submission machines connected to large size Grid pools. The pool of work stations are made up of commodity PCs in Table 2 256 Mbytes to 1 Gbytes. The network used to interconnect the nodes to nodes could be Ethernet 100 Mbits/sec. The operating systems used were Linux Red-Hat 9.0, Windows NT5.0, and Windows XP.
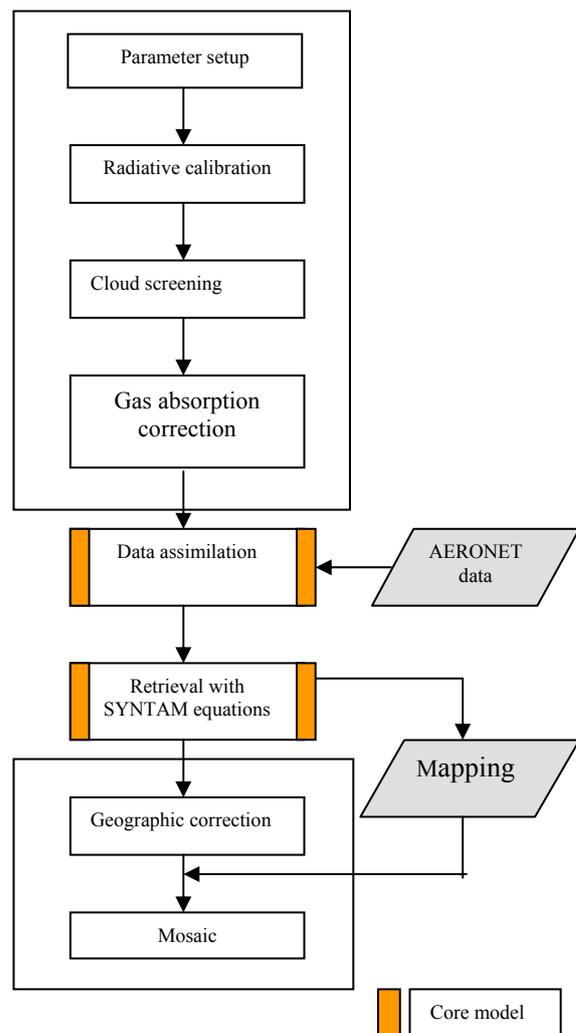
Figure 1. The flowchart of retrieval model

3.2 Experimental results

Map of MODIS derived aerosol optical thickness at 550 nm and of the China Land on Mar 19, 2008 is presented in Figure 2. Figure 3 shows the Angstrom wavelength a for the same time period derived by the model. Verification was performed using these retrieved products. We successfully produced 4 GBytes of aerosol property products within 5 hours.

(a) Terra overpass (am 10:30am)

(b) Aqua overpass (2:30pm)
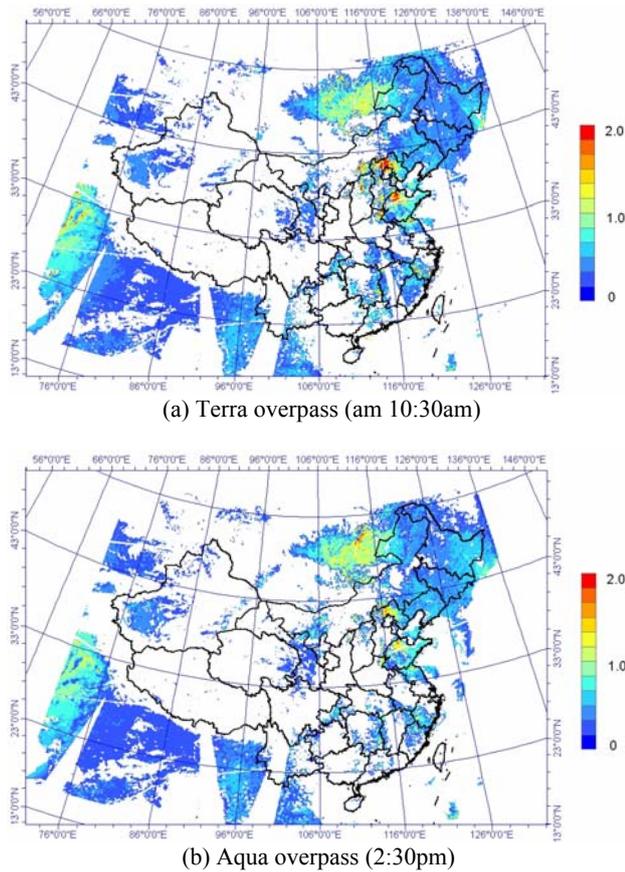
Figure 2. Map of MODIS derived aerosol optical thickness at 550 nm of the China land on March 19, 2008.
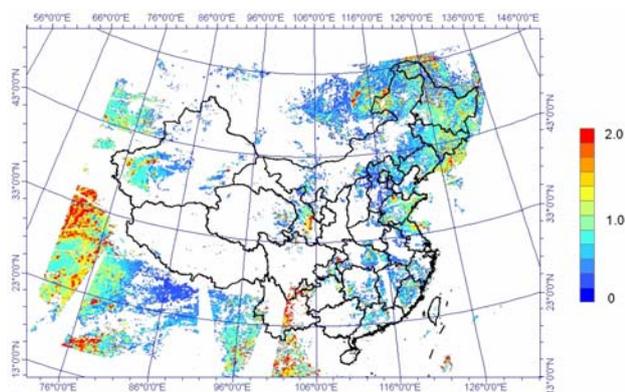
Figure 3. Map of MODIS derived Angstrom parameters wavelength α at 470-660 nm of the China land on March 19, 2008.

4. CONCLUSION

The long term goal is to develop AOD climate from MODIS data suitable for climate change analysis. This paper describes the progress for this goal. A methodology using multi-resource remotely sensed data and adapting available aerosol retrieval model in a Grid environment is demonstrated. Experimental results are presented in a realistic application, using data collected by MODIS over China land. Derived result and computing performance of the proposed algorithm is given using the Grid test-bed at the Institute of Remote Sensing Applications of Chinese Academy of Sciences (IRSA, CAS). Combined, the experimental results show that Grid-enabled model allowed on-demand large volume of ground-based data assimilation with parameters, and achieved substantial reductions in computational times. The research gives a thoughtful perspective on the potential of applying high performance computing practices to remote sensing quantitative retrieving problems.

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