ARTICLE IN PRESS

RSE-10057; No of Pages 20

Remote Sensing of Environment xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A Cloud masking algorithm for the XBAER aerosol retrieval using MERIS data

Linlu Mei [a,*], Marco Vountas [a], Luis Gómez-Chova [b], Vladimir Rozanov [a], Malte Jäger [a], Wolfhardt Lotz [a], John P. Burrows [a], Rainer Hollmann [c]

[a] Institute of Environmental Physics, University of Bremen, Germany
[b] Image Processing Laboratory, University of Valencia, Spain
[c] Deutscher Wetterdienst (DWD), Offenbach, Germany

ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form 25 August 2016
Accepted 17 November 2016
Available online xxxx

Keywords:
Cloud mask
Aerosol
MERIS
XBAER

ABSTRACT

To determine aerosol optical thickness, AOT, and other geophysical parameters describing conditions in the atmosphere and at the earth's surface by inversion of remote sensing measurements from space based instrumentation, it is necessary to separate ground scenes into cloud free and cloudy or cloud contaminated. Identifying the presence of cloud in a ground scene and establishing an accurate and adequate cloud mask is a challenging task. In this study, measurements by the European Space Agency (ESA) MEdium Resolution Imaging Spectrometer (MERIS) have been used to develop a cloud identification and cloud mask algorithm for preprocessing prior to application of the new algorithm called eXtensible Bremen AErosol Retrieval (XBAER), which retrieves AOT. The new XBAER cloud identification and cloud mask algorithm is called XBAER-CM. This uses thresholds of the reflectance and reflectance ratios measured by MERIS at Top Of Atmosphere (TOA).

In this study the parameters used to determine the presence of cloud in ground scenes are i) the brightness of the scenes, ii) the homogeneity or variability of the radiance and iii) cloud height or altitude information. The threshold values used to identify the presence of cloud are selected by using accurate radiative transfer modeling with different surface and atmospheric scenarios. A histogram analysis has been used for different cloud (thin, thick, two-layers, aerosol contaminated cloud), aerosol (dust and biomass burning) and surface scenarios (vegetation, urban, desert and water). Additionally, a snow/ice detection algorithm has been adapted from MerIs Cloud fRation fOr Sciamachy (MICROS) algorithm.

A validation for the resulting cloud mask data products has been undertaken. This comprised i) comparison of regions scenes, which have been manually generated by experts and ii) more global comparison with cloud identification data products from surface synoptic observations (SYNOP) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). As a part of verification and validation, the XBAER-CM results have been shown to be in good agreement with the "manually"-created masks, considered to be the true reference for a set of challenging scenarios. The overall accuracy compared with SYNOP and CALIOP are 84.4% and 83.2%, respectively. The XBAER-CM data product is a standalone data product but valuable for use with algorithms, which retrieve other cloud, aerosol and surface parameters from the measurements of MERIS and the follow on instruments such as Sentinel 3 Ocean and Land Color Instrument (OLCI) now in space.

1. Introduction

Geophysical parameters describing the physical conditions at the earth's surface or in the atmosphere are retrieved from the measurements by nadir sounding passive remote sensing instrumentation. The latter make observations in the solar or thermal infrared spectral regions from orbiting platforms of the earth. Consequently it is necessary to separate ground scenes, which are cloud free and cloudy. Identifying the presence of cloud in a ground scene and establishing an accurate and adequate cloud mask is a challenging task.

Having an adequate cloud mask is an essential pre-processing step prior to the retrieval of geophysical parameters for the surface and atmosphere from passive remote sensing measurements in the solar spectral region (UV/Vis/NIR) from space based instrumentation. Inadequate cloud masking is well known to impact negatively on aerosol remote sensing in the Vis/NIR. In this wavelength range, the reflectances from cloud, high loading aerosol, and/or snow/ice are challenging to separate unambiguously (Istomina et al., 2010). In additional, small-scale spatial structures and temporal variations in surface reflectance

* Corresponding author.
E-mail address: mei@iup.physik.uni-bremen.de (L. Mei).

http://dx.doi.org/10.1016/j.rse.2016.11.016

and emissivity (Simpson and Gobat, 1996) make the assessment and separation of the surface contribution to the top of the atmosphere reflectance or emission a demanding problem.

To derive accurate Aerosol Optical Thickness, AOT, from satellite-borne imaging spectrometers or radiometers, the accurate identification of ground scenes which are cloud free or cloud contaminated or fully clouded is needed. Algorithms to identify cloud need use a combination of tests or criteria which must be neither too conservative ("strict") and limit the amount of data product available nor too lax ("relax") that result in cloud contamination errors in AOT (Martins et al., 2002; Mei et al., 2016).

The current cloud identification or cloud masking algorithms utilized by the aerosol community make use of a priori knowledge and assumptions about the optical and physical properties of clouds for example: (1) Brightness: usually clouds are bright compared to the underlying surface and other atmospheric constituents like aerosols; (2) Temperature: usually clouds are cold compared to the underlying surfaces; (3) Inhomogeneity of reflectance or thermal emission. This results from the fact that clouds properties are more inhomogeneous spatially than those of aerosol and more variable over short periods of time than the reflectance or emission of the underlying surface.

Differences in the brightness of reflectance or temperature between the surface and the clouds are used for cloud detection by determining thresholds. Brightness of reflectance has been used for cloud identification determining threshold levels for Top Of Atmosphere (TOA) reflectances at different wavelengths with predetermined threshold (Lotz et al., 2009). Examples of how brightness temperature threshold in one or several spectral (IR) channels are used for cloud identification is provided in Istomina et al. (2010). The use of the inhomogeneity of a cloud parameter temporally or spatially is also used to identify cloud. The inhomogeneity is quantified by using a time-series (Lyapustin et al., 2008) or spatial variability analysis (Martins et al., 2002).

Optimal cloud identification and cloud masking to facilitate the remote sensing of aerosol optical properties also benefit from identifying the edge of cloud. This results in cloud adjacency effects, which occur in a region around clouds aka "twilight zone" (Koren et al., 2007).

One example of a cloud identification or cloud masking algorithm is the MODerate resolution Imaging Spectroradiometer (MODIS) Dark-Target (DT). It comprises a combination of spatial variability analysis and the measurements of the 1.38 μm channel of MODIS (Levy et al., 2013). The 1.38 μm channel is mainly sensitive to high clouds because it receives large amounts of scattered solar radiance from the high clouds but little from the surface or low level clouds (Gao et al., 1993). Another approach used for cloud identification in the measurements of the MODIS instruments was the introduction of the so called Deep Blue aerosol index which was shown to be able to discriminate between clouds and dust storms (Hsu et al., 2004, 2013). Deep Blue aerosol index utilizes the spectral variability of dust emissivity at 8.6, 11 and 12 μm wavelengths (Hansell et al., 2007). Yet another approach developed for use with MODIS data is the MultiAngle Implementation of Atmospheric Correction (MAIAC) algorithm, which utilizes a time-series together with a reference clear sky image (temporal cloud screening). This provides a better performance compared with MODIS MOD35 cloud mask (Lyapustin et al., 2008).

The analysis of changes in time of the reflectance at different wavelengths has been proven to be an effective method to identify cloud (Saitwal et al., 2003). Instruments providing dual/multi angle observations also use the knowledge of the angular-dependent radiance value of clouds to identify cloud and derive a cloud mask (e.g. Kahn et al., 2007).

The ESA, European Space Agency, Medium Resolution Imaging Spectrometer, MERIS, provided a set of data comprising stable and well-calibrated Top Of Atmosphere (TOA) reflectances. MERIS flew on the ESA ENVISAT platform, which orbited the earth in a sun synchronous orbit in descending node with an equator crossing time of 10:00 am. ENVISAT delivered measurements from MERIS and its other instrument payload for 10 years (2002 − 2012). The multi-spectral single viewing images of MERIS comprise measurements of the upwelling radiation in the range 400 – 900 nm at selected wavelengths. These data have been used to retrieve multitude of geophysical parameters. Up to the present the retrieval of AOT from MERIS is considered to have limited precision and accuracy (de Leeuw et al., 2015).

In comparison to the retrieval of Land Surface Temperature (LST) from Advanced Along-Track Scanning Radiometer (AATSR), which also made measurements from ENVISAT, a better discrimination of the scenes having clouds is required for the retrieval of AOT. For LST, there is no need to separate ground scenes of high aerosol loading (e.g. biomass burning aerosol, industrial pollution or desert dust) from cloudy scenes, but rather the issue is to eliminate all potentially affected cloud contaminated ground scene (Bulgin et al., 2014). The objective of cloud masking for the retrieval of AOT is to discriminate cloud contaminated and cloud free ground scenes and maximize the number of accurate data products available for climate and air quality studies. In this respect cloud masking for aerosol studies is generally more complex than in other fields of remote sensing.

The ESA standard cloud mask product from MERIS is reported to have an accuracy of 93.5% (Bourg et al., 2012), and it has been used in cloud, aerosol, ocean color and other communities (ESA, 2011; Banks and Mélin, 2015; Li et al., 2012). However, in cases of semi-transparent clouds or partially covered pixels, it is difficult to decide if a pixel shall be identified as cloud or not and the standard MERIS cloud mask does not flag all these cases as cloud (Bourg et al., 2012). Some examples of these problematic cases have been analyzed in Trishchenko and Radkevich (2009) over some regions and in Lindstrot et al. (2006a, 2006b) and Li et al. (2006) over specific ground scenes. Fig. 1 shows an example of the MERIS standard cloud mask product, which does not identify ground scenes with thin cloud or over bright surface with large AOT. Those cases are important scenarios for aerosol remote sensing. From the above we conclude that it is valuable for the retrieval of AOT to improve and evolve algorithms for the identification of cloud for ground scenes and the generation of cloud masks for the application to data from MERIS and similar instruments.

The majority of accurate cloud masks for the MERIS instrument utilized image processing techniques like Bayesian methods, fuzzy logic, artificial neural networks and kernel methods (Gómez-Chova et al., 2010). These statistical learning methods are capable of learning complex data relations and provide fast predictions, however, their performance critically depends on the available data (observations and ground truth) used to train the models. Therefore, the lack of a comprehensive training set covering all possible representative scenarios, which is specially difficult to obtain for cloud masking, may lead to a poor representativeness and generalization when applied to new scenes. Previous studies showed the possibility to obtain accurate cloud mask algorithms for MERIS by combining the characterization of different cloud properties such as the Oxygen-A absorption (Preusker et al., 2006) and surface reflectance features (Simpson and Gobat, 1996).

There have been previous attempts to develop a cloud masking algorithm for MERIS aerosol retrieval algorithm. For example, the Bremen AErosol Retrieval (BAER) algorithm implemented three criteria (brightness, spectral neutrality and inhomogeneity) with threshold values from previous publications or based on one limited scenario (von Hoyningen-Huene et al., 2011). The BAER cloud mask algorithm was proven to work for optically thick clouds but had obvious problems for relatively thin ones (Mei et al., 2016).

In a companion paper we present a novel, robust and accurate AOT retrieval for cloud free scene, which is applied to MERIS data to deliver AOT as a data product (Mei et al., 2016). This algorithm is called the eXtensible Bremen Aerosol Retrieval (XBAER). In this paper we describe XBAER-CM algorithm which identifies cloud and generates a cloud mask when applied to MERIS data. As described below, the XBAER-CM

Please cite this article as: Mei, L., et al., A Cloud masking algorithm for the XBAER aerosol retrieval using MERIS data, Remote Sensing of Environment (2016), http://dx.doi.org/10.1016/j.rse.2016.11.016