Journal of Quantitative Spectroscopy & Radiative Transfer 116 (2013) 122–131

Contents lists available at SciVerse ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

A fast radiative transfer model for visible through shortwave infrared spectral reflectances in clear and cloudy atmospheres

Chenxi Wang [a,*], Ping Yang [a], Shaima L. Nasiri [a], Steven Platnick [b], Bryan A. Baum [c], Andrew K. Heidinger [d], Xu Liu [e]

[a] Department of Atmospheric Sciences, Texas A&M University, College Station, TX 77843, USA
[b] Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[c] Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706, USA
[d] NOAA/NESDIS Center for Satellite Applications and Research, Madison, WI 53706, USA
[e] Science Directorate, NASA Langley Research Center, Hampton, VA 23681, USA

ARTICLE INFO

Article history:
Received 14 July 2012
Received in revised form
12 October 2012
Accepted 15 October 2012
Available online 23 October 2012

Keywords:
Radiative transfer
Cloud remote sensing
Fast radiative transfer model
Non-Lambertian surface
Twisted icosahedral mesh
Adding-doubling

ABSTRACT

A computationally efficient radiative transfer model (RTM) for calculating visible (VIS) through shortwave infrared (SWIR) reflectances is developed for use in satellite and airborne cloud property retrievals. The full radiative transfer equation (RTE) for combinations of cloud, aerosol, and molecular layers is solved approximately by using six independent RTEs that assume the plane-parallel approximation along with a single-scattering approximation for Rayleigh scattering. Each of the six RTEs can be solved analytically if the bidirectional reflectance/transmittance distribution functions (BRDF/BTDF) of the cloud/aerosol layers are known. The adding/doubling (AD) algorithm is employed to account for overlapped cloud/aerosol layers and non-Lambertian surfaces. Two approaches are used to mitigate the significant computational burden of the AD algorithm. First, the BRDF and BTDF of single cloud/aerosol layers are pre-computed using the discrete ordinates radiative transfer program (DISORT) implemented with 128 streams, and second, the required integral in the AD algorithm is numerically implemented on a twisted icosahedral mesh. A concise surface BRDF simulator associated with the MODIS land surface product (MCD43) is merged into a fast RTM to accurately account for non-isotropic surface reflectance. The resulting fast RTM is evaluated with respect to its computational accuracy and efficiency. The simulation bias between DISORT and the fast RTM is large (e.g., relative error $>5\%$) only when both the solar zenith angle (SZA) and the viewing zenith angle (VZA) are large (i.e., SZA$>45^\circ$ and VZA$>70^\circ$). For general situations, i.e., cloud/aerosol layers above a non-Lambertian surface, the fast RTM calculation rate is faster than that of the 128-stream DISORT by approximately two orders of magnitude.

1. Introduction

Fast forward radiative transfer models (RTMs) implemented for specific satellite-based instruments, also known as radiance simulators, are important to the radiance assimilation used in numerical weather prediction (NWP) systems [1–4] and in the operational retrievals of atmospheric profiles [5–7] as well as cloud [8–12] and aerosol [13] properties. While numerous studies focused on the fast radiance calculations in the infrared (IR) region ($\lambda > 4$ μm) [3,5,9–12,14,15], the forward radiance simulations in the IR spectral region are relatively straightforward compared with

---

[*] Corresponding author. Tel.: +1 979 845 5123.
E-mail address: chenx.wang@geos.tamu.edu (C. Wang).

0022-4073/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jqsrt.2012.10.012

those in the visible through shortwave infrared (VIS/SWIR) regimes ($0.4\ \mu m < \lambda < 2.5\ \mu m$). For example, the sources of IR radiances, including thermal emission from the surface, atmosphere, cloud, and aerosol layers, do not show significant angular dependence, and the limited impact of the anisotropic feature of surface reflection can be ignored due to the small albedo [16,17]. Additionally, both cloud and aerosol particles absorb more energy in the IR spectral region [18–22] than in the VIS/SWIR spectral region mitigating relatively complicated scattering effects. In the VIS/SWIR region, however, the "quasi-isotropic" feature of radiance vanishes because of multiple scattering processes within the cloud/aerosol layers and with non-Lambertian surface reflection. Furthermore, the primary radiation source within the VIS/SWIR spectral region is solar radiation, giving rise to an azimuthal angular dependence of the radiance that is caused partially by the quasi-collimated direct solar beam. Consideration of both gaseous absorption and Rayleigh scattering effects makes the implementation of numerical simulation more difficult. If the cloud or aerosol layer is opaque, several of the well-known RTMs [23–27], which deal with the multiple scattering in the cloud and aerosol layers and reflective non-Lambertian surfaces require significant computational effort to simulate the radiance.

A number of challenges exist in the accurate forward simulation of non-clear sky top of the atmosphere (TOA) radiance in the VIS/NIR spectral region. First, the forward radiance simulator requires information about the cloud/aerosol layer, such as geometric height/thickness and optical/microphysical properties, and the atmospheric state, including the temperature, pressure, and humidity profiles. Modern satellite operational products and their corresponding algorithms use a variety of approaches to infer cloud and aerosol layer geometries [28–31], ambient temperature, pressure, and humidity [32,33]. A number of reanalysis products, such as the National Centers for Environmental Prediction/Global Data Assimilation System (NCEP/GDAS; [34]) and the NASA Global Modeling and Assimilation Office/Modern Era Retrospective-analysis for Research and Applications (GMAO/MERRA; [35]), provide near real-time meteorological data that facilitate the forward simulation.

Second, the bidirectional reflectance distribution function (BRDF) of a non-Lambertian surface is needed. The Moderate Resolution Imaging Spectroradiometer (MODIS) operational land surface product (MCD43) provides a series of parameters associated with a forward BRDF model [36,37] to reveal the directional variance of surface reflectance [38,39]. The surface BRDF over the ocean, largely determined by the surface wind speed [40], can also be simulated. The BRDF models for both ocean and land surfaces are well developed and have been validated using satellite-based and in-situ measurements [41]. However, the Lambertian surface assumption is still widely used in current satellite-based cloud retrieval algorithms, such as the ones for MODIS Collection 5 [42], the Spinning Enhanced Visible and Infrared Imager (SEVIRI), and the Advanced Very High Resolution Radiometer (AVHRR) [43].

Although many rigorous radiative transfer schemes, such as the adding–doubling (AD) algorithm [26,27] and the discrete ordinates radiative transfer (DISORT) method [23], have been developed, they require substantial computational effort and are impractical for global satellite remote sensing applications. Thus, it is critical to develop computationally efficient RTM capabilities. In this paper, a computationally stable and efficient AD algorithm is explored that is designed to solve approximately the problem of radiation transfer in scattering and absorbing media (thermal emission is omitted for simplification) above an arbitrary non-Lambertian surface. Two novel features of this algorithm are in its treatment of Rayleigh scattering and an arbitrary number of cloud/aerosol layers and the associated solid angle integration.

To consider separately both the impact of Rayleigh scattering and the cloud/aerosol layers, we divided the full radiative transfer equation (RTE) into six independent subequations [44,45]. The total effect of multiple cloud/aerosol layers is solved numerically using the AD algorithm. The AD algorithm is known to be accompanied by a time consuming integration process over a conjunct solid angle associated with the two adjacent scattering and absorptive layers with the resulting integral known as "star products" [46,47]. One traditional solution is to calculate numerically the integral with a constant zenith–azimuth (select constant values for zenith and azimuth angles) discretization scheme [48]. The use of this discretization scheme in a fast RTM is inappropriate for two reasons. First, the radiance simulations slow down computationally in the zenith (or nadir) direction, i.e., the zenith angle cosine is near 1 (or -1), where the variation of BRDF is not significant. Second, the discrete solid angles in the region where the zenith angle cosine is near zero (i.e., "equator region") are larger than those in the zenith/nadir region with the regular discretization scheme. However, the BRDF always contains obvious variations in the "equator region", and, as a result, the numerical integration can lose significant accuracy. While we note that some AD codes have chosen to circumvent this loss of accuracy by using a constant cosine of zenith angle discretization (i.e., equal solid angle [26]), we have instead selected a twisted icosahedral grid [49] to calculate the integral efficiently.

The remainder of this paper is organized with the Atmosphere–Cloud/Aerosol–Surface system described in Section 2; the analytical solutions of the independent RTEs briefly presented in Section 3; the numerical approach for reducing the computational burden is introduced in Section 4; and, the validation and summary are discussed in Sections 5 and 6, respectively.

2. Scheme of the model

To take advantage of the well-accepted AD technique, the RTE solver is designed for a plane-parallel and vertically inhomogeneous medium above a reflective lower boundary. Specifically, the background consists of two clear layers without cloud or aerosol particles, and a "non-clear" layer containing multiple consecutive cloud or aerosol layers (Fig. 1), each of which is assumed to contain a homogeneous absorbing and/or scattering medium such that the spectral single-scattering albedo and phase functions are constant. The Rayleigh scattering between any two consecutive cloud/aerosol layers is neglected for simplicity. The extinction caused by the clear-sky layer between the surface and the