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Validation of the community radiative transfer model

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ABSTRACT

To validate the Community Radiative Transfer Model (CRTM) developed by the U.S. Joint Center for Satellite Data Assimilation (JCSDA), the discrete ordinate radiative transfer (DISORT) model and the line-by-line radiative transfer model (LBLRTM) are combined in order to provide a reference benchmark. Compared with the benchmark, the CRTM appears quite accurate for both clear sky and ice cloud radiance simulations with RMS errors below 0.2 K, except for clouds with small ice particles. In a computer CPU run time comparison, the CRTM is faster than DISORT by approximately two orders of magnitude. Using the operational MODIS cloud products and the European Center for Medium-range Weather Forecasting (ECMWF) atmospheric profiles as an input, the CRTM is employed to simulate the Atmospheric Infrared Sounder (AIRS) radiances. The CRTM simulations are shown to be in reasonably close agreement with the AIRS measurements (the discrepancies are within 2 K in terms of brightness temperature difference). Furthermore, the impact of uncertainties in the input cloud properties and atmospheric profiles on the CRTM simulations has been assessed. The CRTM-based brightness temperatures (BTs) at the top of the atmosphere (TOA), for both thin ($\tau < 5$) and thick ($\tau > 30$) clouds, are highly sensitive to uncertainties in atmospheric temperature and cloud top pressure. However, for an optically thick cloud, the CRTM-based BTs are not sensitive to the uncertainties of cloud optical thickness, effective particle size, and atmospheric humidity profiles. On the contrary, the uncertainties of the CRTM-based TOA BTs resulting from effective particle size and optical thickness are not negligible in an optically thin cloud.

1. Introduction

Satellite-based observations across the visible, infrared, and microwave spectral regions provide valuable information on clouds, which cover, on an average, approximately 70% of the globe. However, most satellite measurement assimilation approaches have focused on satellite data for clear-sky conditions [1]. Since clouds are dominant in regions undergoing quickly changing weather conditions, a rational and computationally efficient method to use satellite cloud information is needed. Numerical weather prediction (NWP) models could use such a method to enhance the simulation and forecasting capabilities under both clear and cloudy conditions [2–6]. To include cloudy conditions, satellite radiance data assimilation must have an efficient and accurate forward radiative transfer model to handle water and ice cloud particle absorption and multiple radiation scattering. The development of the Community Radiative Transfer Model (CRTM) and its subsequent improvements have created a better method

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for NWP models to assimilate satellite measurements made under all weather conditions.

The CRTM was developed by the U.S. Joint Center for Satellite Data Assimilation (JCSDA) to provide fast, accurate satellite radiance simulations and Jacobian calculations at the top of the atmosphere (TOA) under all weather and surface conditions [7]. The model has undergone substantial improvement and expansion, since the first version was released in 2004. The CRTM has been used in the NOAA/NCEP data assimilation system for supporting weather forecasting, in the NOAA/NCEP and the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO) reanalysis, and in other satellite-based radiance data applications [8]. The CRTM supports the simulation of sensor measurements covering wavelengths ranging from the visible through the microwave.

The infrared (IR) high spectral resolution sounder whose measurements can be simulated by the CRTM has attracted significant attention. High spectral resolution measurements are used to derive vertical profiles of atmospheric temperature, water vapor, trace gases, such as ozone and methane, cloud properties such as cloud top pressure, and Earth surface properties. The atmospheric soundings are produced at higher vertical resolutions and with greater accuracy than those from broadband sounders, such as the High Resolution Infrared Radiometer Sounder (HIRS) and the Geostationary Operational Environmental Satellite (GOES) Sounder. The operation of the Atmospheric Infrared Sounder (AIRS) [9] and the Infrared Atmospheric Sounding Interferometer (IASI) [10], aboard the Aqua and MetOp polar orbiting satellites, respectively, has proved successful. These high spectral resolution IR sounders have thousands of channels with spectral widths narrower than one wavenumber. The spectrally resolved radiance data observed by AIRS and IASI contains a wealth of information about the atmosphere and the Earth's surface and provides an unprecedented opportunity to significantly advance our knowledge of the earth–atmosphere system. The accurate vertical sounding information is important for nowcasting, NWP, and many other applications. Recent studies have demonstrated the high spectral resolution IR sensors can be used to monitor low-level atmospheric activities and to substantially enhance the forecasting of mesoscale and regional severe weather events, including tropical storms and hurricanes [11–13].

The availability of the products based on AIRS and IASI observations with collocated MODIS and other cloud products provide an opportunity to validate the CRTM. The intent of the present study is to provide an assessment of the CRTM simulation of high spectral resolution capabilities for ice cloud scenarios and to improve the model based on a better understanding of the physics involved.

Two approaches are used to validate the CRTM-based high spectral brightness temperatures. The first approach, the model-to-model method, is a rigorous model based on a combination of the Line-By-Line Radiative Transfer Model (LBLRTM) [14] and the Discrete Ordinate Radiative Transfer (DISORT) [15] model and was developed to provide reference simulations under both clear sky and ice cloud conditions. Subsequently, the brightness temperatures (BTs) from the reference model are compared to the CRTM-based, with IASI spectral resolution, upwelling spectral BTs at the TOA. The sensitivity of the simulated BTs to the ice cloud macrophysical and microphysical properties is investigated. In the second approach, the CRTM simulations are compared directly with AIRS observations.

We have organized the paper into six sections. Section 2 briefly describes the three radiative transfer models used in this study: CRTM, LBLRTM, and DISORT. The single-scattering properties of ice clouds are discussed in Section 3. In Section 4, we compare the simulated high spectral brightness temperatures from the reference model (LBLRTM+DISORT) with the CRTM, and further investigate the sensitivity of brightness temperatures to cloud macrophysical and microphysical properties. In Section 5, the simulated radiances from the CRTM, using the operational MODIS cloud products and the ECMWF atmospheric profiles, are compared with those measured from an AIRS. A summary discussion is given in Section 6.

2. Data and models

2.1. The community radiative transfer model (CRTM)

The CRTM is a state-of-the-art satellite radiance simulator including both a forward model, which simulates the upwelling radiances for a given sensor, and its Jacobian, which calculates the radiance derivatives with respect to the input atmospheric state variables [7]. Under all atmospheric and surface conditions [5], the CRTM is capable of accounting for the absorption of atmospheric gases as well as the multiple scattering of water clouds, of ice clouds composed of a variety of nonspherical habits, and of a variety of aerosols. To be more specific, the CRTM includes four major modules to handle atmospheric transmittance, surface properties including albedo and emissivity, cloud and aerosol optical properties and radiative transfer [5]. The atmospheric transmittance module uses a fast model, the Optical Path TRANsmittance (OPTRAN) model, to compute the gaseous absorption for the given pressure, temperature, water vapor, and ozone concentration profiles [7]. The surface emissivity/reflectivity module consists of ocean, land, snow, and ice surface components and is further divided into smaller modules according to the spectral region and surface sub-type. In the cloud/aerosol module, six cloud and eight aerosol types are included with pre-computed optical property lookup tables (LUTs). The cloud/aerosol module includes: water and rain cloud types; ice, graupel, snow, and hail cloud types defined by their cloud particle densities: 0.9, 0.4, 0.1, and 0.9 g cm^{-3}; and, the aerosol types of dust, dry organic carbon (OC), wet OC, dry black carbon (BC), wet BC, sea salt accumulation mode (SSAM), sea salt coarse mode (SSCM), and sulfate. The cloud/aerosol module can be used for multiple cloud/aerosol layers in a vertical column [5]. The advanced fast doubling–adding method, described in detail by Liu and Weng [16], is used in the radiative transfer module to solve the radiative transfer equation.

2.2. LBLRTM+DISORT model

Accurate simulations of thermal IR radiances at the TOA must account for the gaseous absorption in the