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Validation of clear-sky radiances over oceans simulated with MODTRAN4.2 and global NCEP GDAS fields against nighttime NOAA15-18 and MetOp-A AVHRR data

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ABSTRACT

An accurate and globally representative forward radiative transfer model (RTM) is needed to explore improvements in sea surface temperature (SST) retrievals from spaceborne infrared observations. This study evaluates the biases in top-of-atmosphere (TOA) brightness temperatures (BT) modeled with the moderate resolution transmission (MODTRAN4.2) band RTM, bounded by a Fresnel's reflective flat sea surface. This model is used to simulate global clear-sky Advanced Very High Resolution Radiometer (AVHRR) nighttime BTs from NOAA-15 through 18 and MetOp-A platforms for one full day of 18 February 2007. Inputs to RTM (SST fields and vertical profiles of atmospheric relative humidity, temperature, pressure, and geopotential height) are specified from the National Centers for Environmental Prediction's (NCEP) Global Data Assimilation System (GDAS) data. Model BTs in AVHRR channels 3B (3.7 μm), 4 (11 μm), and 5 (12 μm) are then compared with their respective measured counterparts, available in the NESDIS operational SST files. Ideally, the RTM should match the observations, but in fact, the modeled BTs are biased high with respect to the AVHRR BTs. The “Model minus Observation” (M − O) bias ranges from about 0 to 2 K, depending upon spectral band, view zenith angle, and sea and atmosphere state at the retrieval point. The bias asymptotically decreases towards confidently clear-sky conditions, but it never vanishes and invariably shows channel-specific dependencies on view zenith angle and geophysical conditions (e.g., column water vapor and sea–air temperature difference). Fuller exploration of the potential of the current RTM (e.g., adding global vertical aerosol profiles) or improvements to its input (NCEP SST and atmospheric profiles) may reduce this bias, but they cannot fully reconcile its spectral and angular structure. The fact that the M−O biases are closely reproducible for five AVHRR sensors flown onboard different platforms adds confidence in the validation approach employed in this study. We emphasize the need for establishing a globally adequate forward RTM for the use in SST modeling and retrievals. A first test of the RTM adequacy is its ability, when used in conjunction with the global fields from the numerical weather prediction models, to reproduce the TOA clear-sky radiances measured by satellite sensors.

1. Introduction

Sea surface temperatures (SST) are derived from measurements in the infrared window channels using either regression or physical algorithms. Regression-based multi-channel (MCSST) and non-linear (NLSST) techniques have been in operational use since the 1980s and 1990s, respectively, with the data from the Advanced Very High Resolution Radiometers (AVHRR) flown onboard NOAA satellites (McClain et al., 1985; Walton et al., 1998). They continue to be employed for SST retrievals from the Moderate Resolution Imaging Spectroradiometers (MODIS) flown onboard Terra and Aqua satellites (Brown & Minnett, 1999) and will also be used with the data from the Visible and Infrared Imager/Radiometer Suite (VIIRS) to be flown onboard the future National Polar-orbiting Operational Environmental Satellite System (NPOESS) (Sikorski et al., 2002). Coefficients of regression algorithms are customarily derived empirically against in-situ SSTs and sometimes theoretically using radiative transfer model (RTM) simulations (cf., Merchant et al., 1999). Physical retrieval algorithms based on solving the radiative transfer equation in each retrieval point have been also proposed (e.g., Susskind et al., 1984; Uddstrom & McMillin, 1994) but not shown to outperform the simple regression techniques, in an operational setting. Globally representative and accurate RTM, carefully validated against collocated satellite measurements, is the key to the improvements in all these SST retrieval techniques.

In this study, a forward RTM is tested based on the Moderate Resolution Transmission (MODTRAN4.2) band model (Berk et al., 2000). MODTRAN was selected for these analyses because this RTM has been long publicly available and its heritage traces back to

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LOWTRAN. Both RTMs have been widely used for a variety of remote sensing analyses and applications, mainly from wide-band satellite imagers. In particular, different versions of MODTRAN/LOWTRAN have been evaluated for the analyses of SST retrievals from the heritage sensors (e.g., Deschamps and Phulpin, 1980; Barton et al., 1989; Francois et al., 2002; Merchant and Le Borgne, 2004). More recently, MODTRAN4.2 has been also employed for the development of SST algorithm for the VIIRS instrument onboard the future national polar system, NPOESS (Sikorski et al., 2002).

Water vapor spectroscopy is the key for the radiative transfer in the window regions. MODTRAN4.2 uses the CKD2.4 water vapor continuum (Clough et al., 1989) and HITRAN 2000 database for lines (Rothman et al., 2003). Merchant et al. (1999) identified the need for improvement in the earlier versions of the CKD. In recent years, most RTMs have switched over to an advanced MTCKD formulation (e.g., Saunders et al., 2007). In this study, we have chosen to validate the MODTRAN4.2 RTM "as is", as an average user of this RTM would do. We believe that these validation results are of interest for a wide range of remote sensing practitioners, including those who use this RTM for SST analyses.

To satisfy the requirement of global representativeness, spectral atmospheric transmittances and upwelling and downwelling radiances are calculated using vertical profiles of relative humidity (RH), temperature (T), pressure (P), and geopotential height (GH) specified from the National Centers for Environmental Prediction's (NCEP) Global Data Assimilation System (GDAS). Spectral emissivity for a flat surface is modeled outside MODTRAN, using Fresnel's equations and Snell's law, from the complex refractive index of water. The spectral atmospheric parameters and emissivities are calculated for a given sensor view geometry at a step of 1 cm^{-1} and substituted into the radiative transfer equation, along with the Reynolds–Smith bulk SST corrected for the skin-bulk difference using the wind speed dependent parameterization of Donlon et al. (2002). The resulting top-of-atmosphere (TOA) spectral radiances are convolved with the channel spectral response functions and converted to brightness temperatures (BT). Extraterrestrial radiation, scattering effects, and reflectance from a wind-roughened surface are not considered in the current RTM. Sensitivity to aerosols is preliminarily checked using literature review and calculations with the "navy maritime" model available in MODTRAN4.2.

The key element of this study is validation of this forward RTM against observed nighttime clear-sky AVHRR BTs obtained from the NESDIS operational SST system. The comparisons are made in three infrared (IR) channels, 3B (3.7 μm), 4 (11 μm), and 5 (12 μm), for five AVHRR/3 sensors flown onboard NOAA-15 through 18 and MetOp-A platforms, which overpass at night between approximately 9:30 pm and 5:20 am local equator crossing time. The objective is to see if the RTM simulations match the AVHRR BTs. Of particular interest to us is whether the RTM can reproduce the observed spectral, angular, and geophysical (water vapor, SST, sea–air temperature difference, wind speed) dependencies in AVHRR BTs that are critically important for SST retrievals. All analyses are performed for two types of surfaces, blackbody and flat Fresnel's reflector, to quantify the effect of emissivity on the M−O bias. Including emissivity in the RTM indeed brings it closer to the AVHRR in all bands; however, the RTM remains biased high and still does not fully reproduce the major trends in the AVHRR BTs. The magnitude of the bias is reduced towards confidently clear-sky conditions, but the discrepancy still persists. The spectral and angular structure of the bias suggests that it cannot be fully attributed to possible incompleteness of the employed RTM (e.g., missing aerosol or wind-effects) or errors in the NCEP GDAS input. Furthermore, the fact that the bias is consistent across five sensors adds confidence in its validity and calls for improvements in the forward RTM before it can be used to explore improvements in SST retrievals.

The paper is organized as follows. Section 2 describes the forward RTM, including the implementation of MODTRAN4.2 with NCEP GDAS data, and the calculation of surface emissivity. It also compares spectral emissivity modeled in this study with the results of Masuda et al. (1988) and quantifies the effect of surface emissivity on the TOA BTs as a function of view zenith angle. Section 3 introduces the RTM validation approach. It also describes the AVHRR data used here as the validation standard and the procedure to collocate them in space and time with the RTM/NCEP simulations. Section 4 analyzes the M−O biases for two surfaces (blackbody and Fresnel's), and Section 5 summarizes and concludes this study.

2. Forward radiative transfer model (RTM) and input data

Assuming that there is no extraterrestrial radiation at night, scattering in the atmosphere is negligible and sea surface is flat, the spectral TOA clear-sky IR radiance is given as:

$$R^{\mathrm{TOA}}(i,\theta) = \underbrace{\varepsilon(i,\theta)\cdot B(i,T_{\mathrm{sfc}})}_{\text{surface}}\cdot \underbrace{\tau^{\uparrow}(i,\theta)}_{\text{atmosphere}} + \underbrace{L^{\uparrow}(i,\theta)}_{\text{atmosphere}} + \underbrace{(1-\varepsilon(i,\theta))}_{\text{surface}} \times \underbrace{L^{\downarrow}(i,\theta)\cdot\tau^{\uparrow}(i,\theta)}_{\text{atmosphere}} \tag{1a}$$

Here, θ is the view zenith angle (measured at the surface), 'i' denotes wavenumber interval (1 cm^{-1}, as determined by the MODTRAN4.2 band model, Berk et al., 1998), T_{sfc} is the skin SST, ε is the surface emissivity, B is the Planck radiance, $\tau^{\uparrow}$ is the atmospheric transmittance in the forward direction, and $L^{\uparrow}$ and $L^{\downarrow}$ are the atmospheric upwelling and downwelling radiances, respectively. The origin of each term is annotated below the braces.

The TOA spectral radiances computed at 1 cm^{-1} interval using Eq. (1a) are convolved with the relative spectral response (RSR, or Φ_i, also digitized at a step of 1 cm^{-1}) to calculate the TOA radiance in a sensor channel:

$$R^{\mathrm{TOA}}_{\mathrm{channel}}(\theta) = \sum_{i=\nu_1}^{\nu_2} R^{\mathrm{TOA}}(i,\theta)\cdot\Phi_i \Big/ \sum_{i=\nu_1}^{\nu_2}\Phi_i \tag{1b}$$

The RSRs (normalized at RSR$_{\max}$=1) are available in Goodrum et al., 2003 (for NOAA-15 to -18) and in ITT, 2007 (for MetOp-A). (They have been also summarized at http://www.star.nesdis.noaa.gov/smcd/spb/

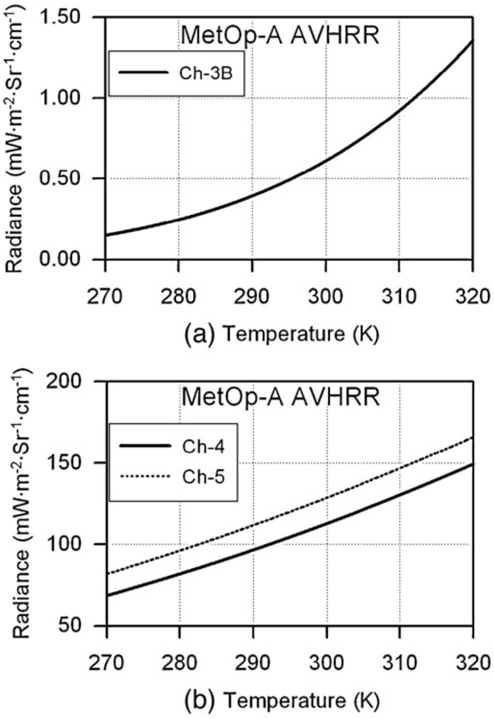

Fig. 1. Temperature to radiance conversion look-up tables for MetOp-A AVHRR channels (top) 3B; (bottom) 4 and 5.