Experiments with Cloud Properties: Impact on Surface Radiative Fluxes

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ABSTRACT

Solar radiation reaching the earth's surface provides the primary forcing of the climate system, and thus, information on this parameter is needed at a global scale. Several satellite-based estimates of surface radiative fluxes are available, but they differ from each other in many aspects. The focus of this study is to highlight one aspect of such differences, namely, the way satellite-observed radiances are used to derive information on cloud optical properties and the impact this has on derived parameters such as surface radiative fluxes. Frequently, satellite visible radiance in a single channel is used to infer cloud transmission; at times, several spectral channels are utilized to derive cloud optical properties and use these to infer cloud transmission. In this study, an evaluation of these two approaches will be performed in terms of impact on the accuracy in surface radiative fluxes. The University of Maryland Satellite Radiation Budget (UMD/SRB) model is used as a tool to perform such an evaluation over the central United States. The estimated shortwave fluxes are evaluated against ground observations at the Atmospheric Radiation Measurement Program (ARM) Central Facility and at four ARM extended sites. It is shown that the largest differences between these two approaches occur during the winter season when snow is on the ground.

1. Introduction

Solar radiation incident at the earth's surface determines the surface temperature and sensible and latent heat fluxes that govern most of the dynamical and hydrological processes (Stephens and Greenwald 1991). It plays an essential role in controlling biological processes (Running et al. 1999; Platt 1986) and is also needed for validating climate models (Garratt et al. 1993; Wild et al. 1995; Wielicki et al. 2002). Clouds strongly interact with solar and terrestrial radiation and thus modulate the energy balance of the earth and the atmosphere as estimated from satellites (Ramanathan 1987; Ramanathan et al. 1989) and from numerical models (Ramanathan et al. 1983; Cess et al. 1989). The largest uncertainties in surface shortwave (SW) flux estimates from satellites are due to inadequate information on cloud properties. There have been many attempts at both regional and global scales to estimate surface radiative fluxes from satellite-observed radiances (Ramanathan 1986; Pinker and Laszlo 1992; Li and Leighton 1993; Stephens et al. 1994; Gupta et al. 1999; Mueller et al. 2004; Raschke et al. 1991; Rigollier et al. 2004; Whitlock et al. 1995; Lefèvre et al. 2007). Most models have been designed for use with a particular satellite and, frequently, cloud optical properties are inferred from a single visible channel. The use of multichannel information is expected to provide a more accurate description of cloud optical properties and, subsequently, lead to improved estimates of surface solar fluxes. In this study, the effect of cloud optical properties as derived by two independent methods (a single-channel or a two-channel approach) on the estimation

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of surface shortwave fluxes is evaluated. The University of Maryland Satellite Radiation Budget (UMD/SRB) model is used as a tool to perform such an evaluation. The original version of the model (model A) utilizes the visible channel (0.52–0.72 μm) of the Geostationary Operational Environmental Satellite (GOES) to infer cloud optical depth. The National Aeronautics and Space Administration (NASA) Langley Cloud and Radiation Research Group derives cloud optical depth over the Atmospheric Radiation Measurement (ARM) Program Southern Great Plains (SGP) region from multiple channels of GOES. To use such information directly in the UMD/SRB model, it is necessary to redesign model A. The modified version will be labeled model B. The independently derived cloud properties provided by the NASA Langley group (Minnis et al. 2002) over the ARM SGP site will be used to drive this version of the inference scheme. The resulting surface shortwave fluxes from both versions are compared with ground observation at the ARM Central Facility, as well as at four extended ARM sites. In section 2, models A and B are described. Data used are discussed in section 3. Results are presented in section 4, and a summary is presented in section 5.

2. Model description

Model A is a physical inference scheme based on radiative transfer theory (Pinker et al. 2003). Using forward radiative transfer calculations, relationships are established between the broadband (0.2–4.0 μm) transmissivity and the reflectivity at the top of the atmosphere (TOA) under various conditions pertaining to the surface, atmosphere, and clouds. The radiative fluxes at the surface and at the top of the atmosphere are computed by determining the atmospheric transmission and reflection and the surface albedo pertaining to a particular satellite observation. First, surface albedo is derived from satellite-measured radiances at the TOA that represent average clear-sky conditions. Once the surface albedo is determined, the atmospheric transmission and reflection (optical functions) for instantaneous clear and cloudy conditions are obtained by matching the broadband TOA albedos with those computed by the radiative transfer model. The retrieved optical functions, along with surface albedo, are used to compute fluxes for clear and cloudy conditions. Finally, clear and cloudy fluxes weighted by the pixel number of clear and cloudy conditions are summed up to obtain all-sky fluxes.

In model B, the need to first estimate surface albedo, aerosol, and cloud properties from the clear or cloudy radiances is bypassed. Instead, information on cloud properties is imported from the (NASA) Langley Cloud and Radiation Research Group products. Additional input parameters on the state of the atmosphere needed to drive the model include aerosols, surface albedo, water vapor, and ozone amount. To isolate the effect of independently derived cloud properties, all the other input parameters are kept the same as those used in model A.

3. Data

The surface radiative fluxes used in the comparison were obtained from version 2.1 of model A (Li et al. 2007; Pinker et al. 2007) and from model B driven with cloud information as obtained from the NASA Langley Cloud and Radiation Research Group.

Version 2.1 of model A is based on an operational real-time scheme (version 1.1) as used at the National Oceanic and Atmospheric Administration/National Environmental Satellite Data and Information Service (NOAA/NESDIS) since January 1996, in support of the Global Energy and Water Cycle Experiment (GEWEX) Continental Scale International Project (GCIP). The primary observing system in these two versions is the visible channel (0.52–0.72 μm) on the GOES satellites, which is a narrowband channel. The radiative fluxes are derived for 0.5° latitude × 0.5° longitude grid cells. The 4-km pixels within a grid cell are classified into cloudy, mixed, and clear pixels. Cloud fraction and mean TOA albedo of clear sky and cloudy sky are then calculated for the grid cell and provided to model A to infer radiative fluxes. Instantaneous, hourly, daily, and monthly mean information on surface downwelling shortwave, top of the atmosphere downward, and upwelling radiative fluxes are provided for an area bounded by 25°–50°N, 70°–125°W. Version 2.1 of model A uses updated calibration of the visible sensor, an improved cloud detection scheme [in particular, better cloud detection over snow (Li et al. 2007; Pinker et al. 2007)], and improved atmospheric input parameters such as ozone (which until now was taken from climatology).

The independently derived cloud properties used as inputs to model B are based on the Visible-Infrared-Solar Infrared-Split Windows Technique (VISST), which is an update of the Solar-Solar Infrared-Infrared method described by Minnis et al. (1995). Each GEOS 4-km pixel is classified as clear or cloudy using a modified version of the cloud identification method (Trepte et al. 1999) developed for the Cloud and Earth's Radiant Energy System (CERES). Cloud properties of cloudy pixels are derived at a half-hourly time scale from 1 January to 31 December 2000 using VISST and then averaged into 0.5° latitude × 0.5° longitude cell boxes. The spatial coverage of the derived cloud properties extends from 32.25°–41.75°N, 91.25°–104.750°W.

Ground observations are taken from the Central Facility and four extended sites of ARM SGP at 1-min intervals. For the Central Facility, the downwelling shortwave irradiance from the ARM Best Estimate (BE) Flux Value Added Product (VAP) is used. The BE Flux VAP uses data available from the three collocated radiometer platforms [Solar and Infrared Radiation Station (SIRS) C1, E13, and Baseline Solar Radiation Network (BSRN)] to determine the best available irradiance measurements (Shi and Long 2002). For extended sites, the downwelling shortwave irradiance is from "sirs1dutt" VAP, which is SIRS measurements with the correction for infrared loss to the diffuse shortwave measurements (Long et al. 2001; Younkin and Long 2003). To match approximately the estimated surface downward shortwave fluxes at a resolution of half a degree, the 1-min point measurements are averaged over a 30-min interval centered at the satellite observations.

4. Results

The ground sites are usually not located in the center of the 0.5° grid cells and therefore they do not necessarily represent the 0.5° grid cell average. Therefore, the estimated fluxes were interpolated into 0.5° grid cells centered at five ground sites using inverse distance weighting interpolation method. For each ground site, the measured downwelling shortwave irradiance was compared with estimates from the two models and bias; the root-mean-square error and correlation coefficient were also computed.

Table 1 shows the evaluation results for model B at the Central Facility for the entire period of 2000. For most months, except for January and December, the correlation coefficient is larger than 0.96. RMSE ranges from 42 to 83 W m^{-2}, which is about 8%–20% relative to the mean of the ground observations. The bias varies from −25 to 21 W m^{-2} (relative value of 0.4%–7%). However, for January and December, the difference between model estimates and ground measurements is relatively large, with correlation coefficients of 0.92 and 0.89, biases of −30 (11%) and −34 (13%) W m^{-2}, and RMSEs of 77 (27%) and 83 (31%) W m^{-2}, respectively.

TABLE 1. Evaluation results of model B for the entire period of 2000 at ARM Central Facility.

Month of 2000	Mean of observation W m^{-2}	Bias W m^{-2} (%)	RMSE W m^{-2} (%)	Corr coeff	No. of observations
Jan	286	−30 (11)	77 (27)	0.92	400
Feb	376	−25 (7)	59 (16)	0.97	446
Mar	356	−8 (2)	62 (17)	0.98	586
Apr	497	−11 (2)	72 (14)	0.97	621
May	512	−2 (1)	71 (14)	0.97	742
Jun	446	9 (2)	83 (19)	0.96	767
Jul	538	21 (4)	81 (15)	0.97	792
Aug	539	21 (4)	61 (11)	0.98	729
Sep	500	7 (2)	42 (8)	0.99	661
Oct	340	−24 (7)	69 (20)	0.97	577
Nov	289	−12 (4)	44 (15)	0.98	511
Dec	267	−34 (13)	83 (31)	0.89	444

It is of interest to understand the relatively larger difference between model estimates and ground observations during the winter months. Figure 1 shows the daily average surface albedo at the Central Facility for December and at Extended Site 1 for January. Surface albedo at the Central Facility was provided by the BE Flux VAP. At Extended Site 1, downwelling and upwelling shortwave irradiances are used to calculate surface albedo. During these two months, one-third of the days had a surface albedo greater than 0.4 indicating snow conditions. Figures 2 and 3 present the scatterplots of estimated fluxes from model B against ground observations at the Central Facility for December and Extended Site 1 for January, respectively. The sample points in the scatterplot are classified into two groups. One consists of cases where surface albedos are less than 0.4 (marked by solid triangles) and the other with surface albedo greater than 0.4 (marked by circles). The two figures clearly show that model B underestimates the surface downward shortwave fluxes when the surface albedo is greater than 0.4; the relatively low correlation coefficient, large negative bias, and large

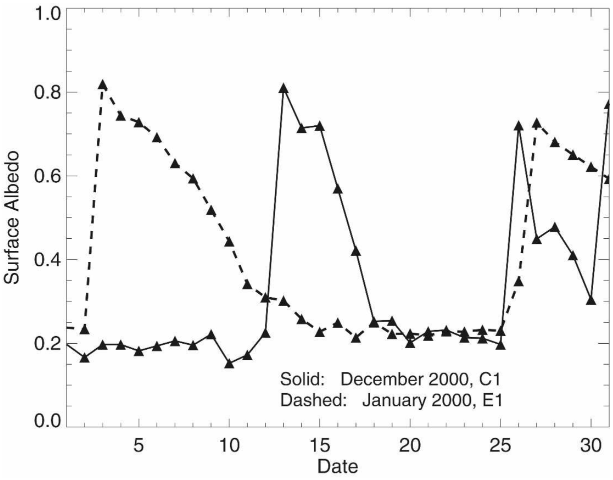

FIG. 1. Daily average surface albedo for December 2000 at the ARM Central Facility and for January 2000 at the Extended Site 1.

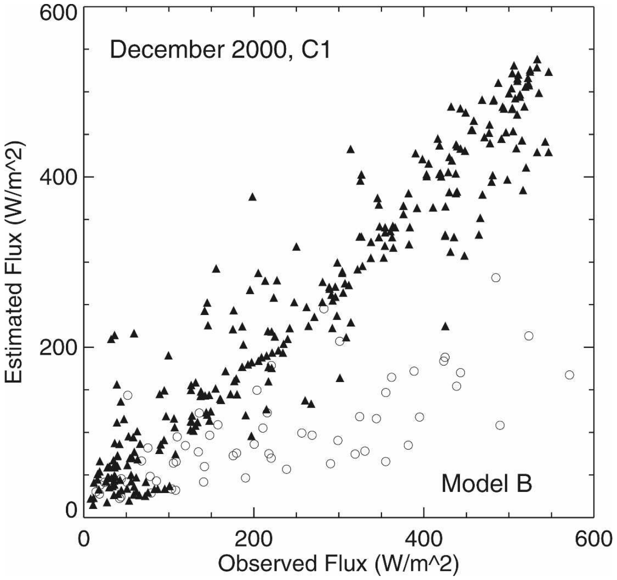

Fig. 2. Evaluation of surface downward SW fluxes estimated from model B as driven with ARM SGP VISST cloud products against ground measurement at ARM Central Facility during December 2000.

RMSE seem to be related to the presence of snow at the surface. Tables 2 and 3 present the evaluation results of models A and B for the two winter months. During December, model A flux estimates have a higher correlation coefficient, smaller rms error, and bias when compared to ground observations at the Central Facility rather than those estimated by model B. At Extended Site 1 for January, fluxes from the two models have the same correlation coefficient while model A fluxes have a smaller bias and RMSE than in model B.

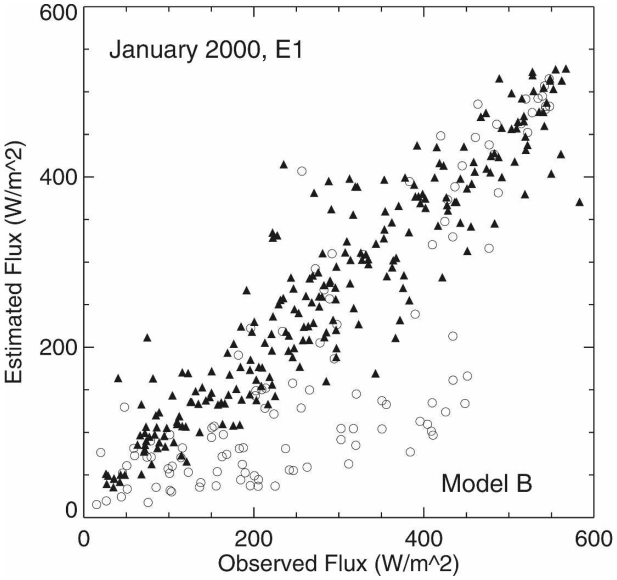

FIG. 3. Same as in Fig. 2, but at Extended Site 1 during January 2000.

TABLE 2. Comparison of evaluation results of models A and B for December 2000 at ARM Central Facility.

Central Facility December	Mean of observation W m^{-2}	Bias W m^{-2} (%)	RMSE W m^{-2} (%)	Corr coeff	No. of observations
Model A	314	−26 (8)	75 (24)	0.89	165
Model B	314	−46 (15)	101 (32)	0.83	165

Figure 4 shows scatterplots of estimated fluxes from models A and B against ground observations at the Central Facility for 2000 (also see Table 4). The 12 months of 2000 are grouped as follows: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). For MAM, JJA, and SON, the corresponding correlation coefficients for model B are 0.97, 0.96, and 0.97, with relative RMSEs of 15%, 14%, and 13% and relative biases of 2%, 3%, and 2%, while model A results have correlation coefficients of 0.95, 0.94, and 0.96, relative RMSEs of 18%, 18%, and 14%, and relative biases of 0.4%, 2%, and 2%. For DJF, the model B correlation coefficient is 0.93, the relative bias is 10%, and the relative RMSE is 22%. For model A the correlation coefficient is 0.92, the relative bias is 5%, and the relative RMSE is 21%.

The satellite estimates at the four extended ARM sites are of similar accuracy as found at the Central Facility. During snow-free periods model B (ARM SGP VISST cloud product) is in better agreement with ground observations than model A while the latter performs better during the winter season.

5. Summary

In recent years, progress has been made in the development and launch of multispectral earth observing systems. Most current estimates of surface SW radiative fluxes are based on geostationary satellites that have the capability to capture the diurnal variation of clouds. Instruments on board such satellites have coarse spectral and spatial resolution and thus are limited in their

TABLE 3. Comparison of evaluation results of models A and B for January 2000 at ARM Extended Site 1.

Extended Site 1 January	Mean of observation W m^{-2}	Bias W m^{-2}	RMSE W m^{-2}	Corr coeff	No. of observations
Model A	338	−27 (8)	92 (27)	0.77	125
Model B	338	−53 (16)	106 (31)	0.77	125

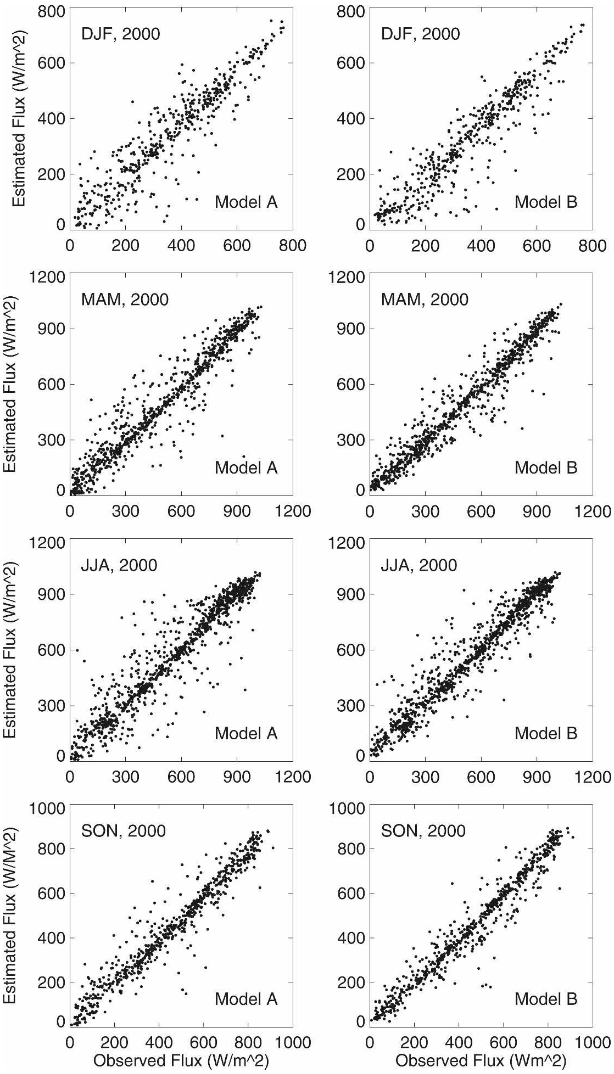

FIG. 4. Same as in Fig. 2, but from models A and B for the year 2000.

capability to accurately detect cloud and/or aerosol optical properties that are important elements of the radiation budget. At the same time, these inference schemes have a tested infrastructure for assessing radiative fluxes. It is therefore of interest to evaluate the ability of these schemes to use independently derived optical parameters that can be obtained from dual- or multichannel observations. The evaluation performed in the present study utilizes cloud properties based on the UMD/SRB model, which uses a single-channel retrieval of cloud optical depth and a multispectral approach provided by the NASA Langley Cloud and Radiation Research Group over the Southern Great Plains. The multispectral approach is more complex than the single-channel one and its applicability in real time is of issue. It is of interest to evaluate the impact of the multichannel approach on estimating surface radiative fluxes. Such an evaluation has been undertaken in this study.

The advanced scheme of the NASA Langley Cloud and Radiation Research Group retrievals should, in principle, lead to more accurate cloud optical properties and a better estimate of surface shortwave fluxes than the simplified inference schemes. Over a 1-yr period, cloud properties derived by this advanced scheme do yield better estimates of surface fluxes during snow-free conditions. During the winter months when snow is on the ground, version 2.1 of model A has a lower RMSE and a smaller bias than model B.

The study also demonstrates the ability of model B to estimate surface fluxes with independent satellite based estimates of cloud optical properties. This is of interest since observations from multichannel systems have the potential to improve estimates of cloud optical parameters. For example, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on board the *Terra* and *Aqua* satellites is a state-of-the-art sensor with 36 spectral bands (King et al. 1992) with demonstrated capabilities to provide high-quality cloud detection and to estimate optical properties of both aerosols and clouds (Kaufman et al. 1997; Platnick et al. 2003). Improvements in estimating surface shortwave fluxes are anticipated from the implementation of model B with cloud and aerosol optical properties from a new

TABLE 4. Summary of the evaluation results of surface downward SW fluxes derived by model A and estimated by model B driven with ARM SGP VISST cloud product against ground measurement at the ARM Central Facility for 2000 as illustrated in Fig. 4.

Season	Mean of observation $\mathrm{W\,m^{-2}}$	No. of observations	Model	Corr coeff	RMSE (%) $\mathrm{W\,m^{-2}}$	Bias (%) $\mathrm{W\,m^{-2}}$
DJF	356	482	A	0.92	74 (21)	−18 (05)
			B	0.93	77 (22)	−34 (10)
MAM	498	831	A	0.95	87 (18)	−2 (00)
			B	0.97	72 (14)	−8 (02)
JJA	549	1000	A	0.94	97 (18)	13 (02)
			B	0.96	79 (14)	19 (03)
SON	456	653	A	0.96	62 (14)	−9 (02)
			B	0.97	58 (13)	−9 (02)

generation of satellite instruments of higher spectral and spatial resolution, such as MODIS on *Terra* and *Aqua* or the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on *Meteosat-8*. Moreover, the evaluation presented here seems timely because of the upcoming A-train satellite constellation that consists of six sun-synchronous satellites and carries advanced instruments that should provide improved information on clouds and aerosols (Stephens et al. 2002).

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