Consistency Check of Cloud Optical Properties Derived from Satellite and Surface Observations

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Introduction

Much work has been done to retrieve both cloud and radiative variables using space-borne observations. Several recent studies also attempted to retrieve cloud optical depth using ground-based radiation measurements. Often, the values of cloud optical depth τ resulting from the two approaches showed considerable discrepancies. For example, Min and Harrison (1996) applied their inversion algorithms to ground-based spectral transmittances observed during the Atmospheric Radiation Measurement (ARM). Their values were compared with those retrieved from Geostationary Operational Environmental Satellite (GOES)-7 and found to be systematically higher. After modifying the calibration of GOES-7 data, Dong et al. (1998) reassessed the satellite retrieval following a similar approach with broadband surface radiation data and found a good agreement for GOES-7, but poor for GOES-8. Barker et al. (1998) retrieved cloud optical depths using 20 years worth of ground pyranometer data collected across Canada. The comparisons between theirs and those from the International Satellite Cloud Climatology Program (ISCCP) CX data set revealed similar systematic differences as reported by Min and Harrison (1996).

In this study, we retrieved cloud optical depths from high temporal resolution (from 1 to 5 minutes) data on ground-based insolation measurements acquired in Canada, the United States, and other parts of the world. The retrieved values are compared to a new-generation ISCCP product, namely the DX data set. The retrieved cloud optical depths were substituted into a radiative transfer model to calculate top of (the) atmosphere (TOA) broadband albedos and fluxes that are then compared with direct observations made by the Earth Radiation Budget Experiment (ERBE), Scanner for Radiation Budget (ScaRaB), and Cloud and Earth's Radiative Energy System (CERES). Such a closure test is instrumental in evaluating the solar radiative transfer model and has certain bearing on the debate regarding cloud absorption anomaly.

Data

Ground radiation measurements were collected under various observation programs. They include the Canadian operational networks operated by the Atmospheric Environmental Service of Canada (Barker et al. 1998); the National Oceanic and Atmospheric Administration's (NOAA's) Surface Radiation Budget Network (SURFRAD) network (DeLuisi et al. 1996); the World Meteorological Organization's (WMO's) Baseline Surface Radiation Network (BSRN) (Ohmura et al. 1998); and the U.S. Department of Energy's (DOE's) ARM Program (Michalsky et al. 1999). Description on the instrumentation and measurement characterization is beyond the scope of this short article. The locations and periods of observation are listed in Table 1. The table also contains information on satellite data that were matched with these ground observations including ISCCP, ERBE, ScaRaB, and CERES. ISCCP DX data were employed for 1993 for the warm season (no snow). Note that ISCCP DX data were employed for 1993, ERBE data from 1988 to 1990, ScaRaB data for 1994 to 1995, and CERES data for 1998. All analyses are limited to snow-free scenes, as determined by satellite scene identification with surface type flagged as snow/ice-free. The data from May to October were analyzed. To ensure that overcast scene as

Table 1. Locations and periods of observation.

No.	Station Name	Operating Agencies	Latitude	Longitude	Observation Period	Satellite Project
1	Port Hardy, B.C.	AES, Canada	50.68°	232.63°	88-90; 93-95	ERBE, ISCCP
2	Resolute	AES, Canada	74.717°	265.017°	88-90,93-95	ERBE, ISCCP
3	Stony Plains	AES, Canada	53.53°	245.99°	88-90; 93-95	ERBE, ISCCP
4	Outlook	AES, Canada	54.483°	252.95°	88-90, 93-95	ERBE, ISCCP
5	Winnipeg	AES, Canada	49.90°	262.77°	88-90; 93-95	ERBE, ISCCP
6	Thompson	AES, Canada	55.75°	262.133°	88-90, 93-95	ERBE, ISCCP
7	Egbert	AES, Canada	44.233°	280.217°	88-90, 93-95	ERBE, ISCCP
8	Dorval	AES, Canada	45.47°	286.25°	88-90; 93-95	ERBE, ISCCP
9	Charlottetown	AES, Canada	46.25°	296.867°	88-90, 93-95	ERBE, ISCCP
10	Goose Bay	AES, Canada	53.30°	299.63°	88-90; 93-95	ERBE, ISCCP
11	ARM SGP CF, Oklahoma	DOE ARM	36.60°	262.52°	94-95, 98	ScaRaB, CERES
12	Boulder	SURFRAD, NOAA	40.216°	254.6°	94-95, 98	ScaRaB, CERES
13	Bondville	SURFRAD, NOAA	40.1°	271.383°	94-95, 98	ScaRaB, CERES
14	Goodwin Creek	SURFRAD, NOAA	34.25°	270.133°	94-95, 98	ScaRaB, CERES
15	Bermuda	BSRN, WMO	32.267°	295.667°	94-95	ScaRaB
16	Kwajalein, Marshall Islands	BSRN, WMO	8.717°	167.733°	94-95	ScaRaB
17	Ilorin	BSRN, WMO	8.533°	4.567°	94-95	ScaRaB
18	Florianopolis	BSRN, WMO	-27.467°	311.517°	94-95, 98	ScaRaB, CERES
19	Spitsbergen	BSRN, WMO	78.93°	11.95°	94-95	ScaRaB
20	Barrow	BSRN, WMO	71.32°	203.60°	94-95	ScaRaB
21	Lindenberg	BSRN, WMO	52.22°	14.12°	94-95	ScaRaB
22	Payerne	BSRN, WMO	46.82°	6.93°	94-95	ScaRaB
23	Tateno	BSRN, WMO	36.05°	140.133°	98	CERES

identified from satellite observations does indeed correspond to overcast situation at surface point, we applied additional conditions based on statistics of surface downward radiation: 30-minute standard deviation for direct, diffuse components must be less than 20 Wm^{-2}, standard deviation of global flux must be less than 28 Wm^{-2}.

Methodology

The method of retrieving cloud optical depth utilizes lookup tables obtained by running an adding-doubling radiative transfer code with 105 spectral bands from 0.2 to 5.0 μm. The tables were generated for different input variables. Sixteen discrete values of τ (0, 1, 2, 4, 8, 12, 16, 20, 24, 32, 48, 64, 96, 128, 196, and 256) were used and solar zenith angle (SZA) was set to be 8.46°, 19.35°, 30.11°, 40.58°, 50.60°, 60.00°, 68.58°, 76.09°, 82.25°, 86.76°, and 89.38°. Different surface albedo models were incorporated including those for evergreen forest, mixed forest surface type, and Lambertian surfaces with varying broadband albedos. Spherical cloud particles were assumed with a radius of 7 μm for water droplets and 20 μm for ice crystals. The retrieval of τ from downwelling irradiance at the surface depends very weakly on cloud particle size (Barker et al. 1998; Li et al. 1999). The lookup tables were created for different atmospheres: SAW, SAS, MLS, MLW, and TRO atmospheres. Interpolation was made according to specific column water vapor amount obtained from National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) REANALYSIS data set (Kalnay et al. 1996). Clouds are placed in different layers with cloud top at 1 km, 4 km, and 9 km. Cloud top heights were determined by an empirical relation between longwave (LW) flux and cloud top height: $H = 22.17-0.085*LW$, where H is in km, LW flux in Wm^{-2}. The relationship was derived from collocated ScaRaB (infrared [IR] window channel) data and atmospheric vertical profiles from the REANALYSIS data set. Minimal cloud top was assumed to be 0.5 km. For ISCCP DX data, cloud top heights were determined from cloud top pressure available from ISCCP archive. Multi-dimensional interpolation was carried out to determine τ, as well as TOA broadband flux and albedo based on surface transmittance, SZA, precipitable water, cloud top height and surface albedo. The resulting TOA estimates are compared with broadband satellite measurements.

Results and Analyses

Figure 1 shows a comparison of retrieved cloud optical depths from ground measurements made in Canada and from ISCCP DX. In contrast to the systematic discrepancy found by Barker with the CX data set, a comparison with DX as shown in Figure 1 is in much better agreement. Moreover, the agreement does not show any dependence on the magnitude of τ. The relatively large scattering stems primarily from the mismatch between surface and satellite observations. Note that the nominal resolution of ISCCP DX data is 30 km, but they actually represent a sample of 4 km, an Advanced Very High Resolution Radiometer (AVHRR) Global Area Coverage (GAC) footprint located inside the 30-km grid but without precise location. This means that the satellite and surface-based retrievals of τ may correspond to quite different cloud scenes. Such a limitation does not, however, hinder much the conclusion of the investigation concerning the systematic discrepancy, as the mismatch affects mainly the scattering. In addition to the pixel values, the frequency histogram concerning the statistics of τ obtained from ISCCP DX and ground observations were compared in Figure 2. Again, the agreement is very close.

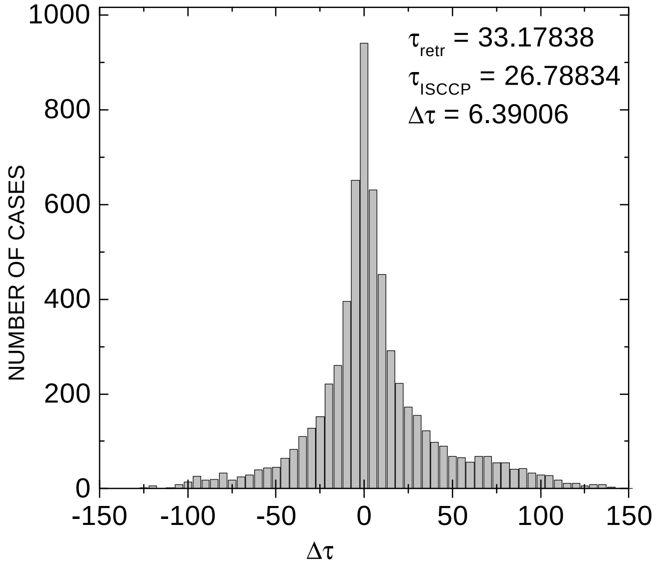

Figure 1. Comparison of ISCCP and surface retrieved τ.

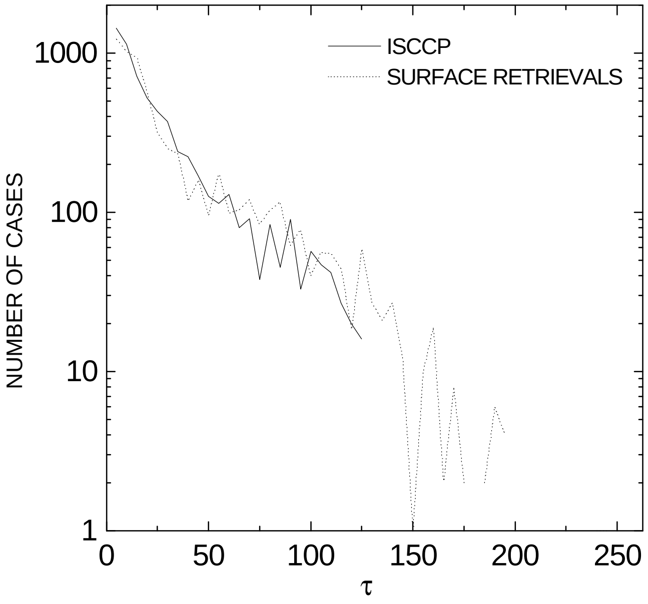

Figure 2. The distribution of optical depth from ISCCP and surface retrievals.

With the retrieved cloud optical depths and ancillary data as described earlier, broadband TOA albedos and fluxes can be computed as well. Comparisons with direct observations are instrumental in evaluating the retrieved cloud optical depths and radiative transfer model that provides the linkage between TOA and surface radiative quantities. Figure 3 presents the comparisons of computed and

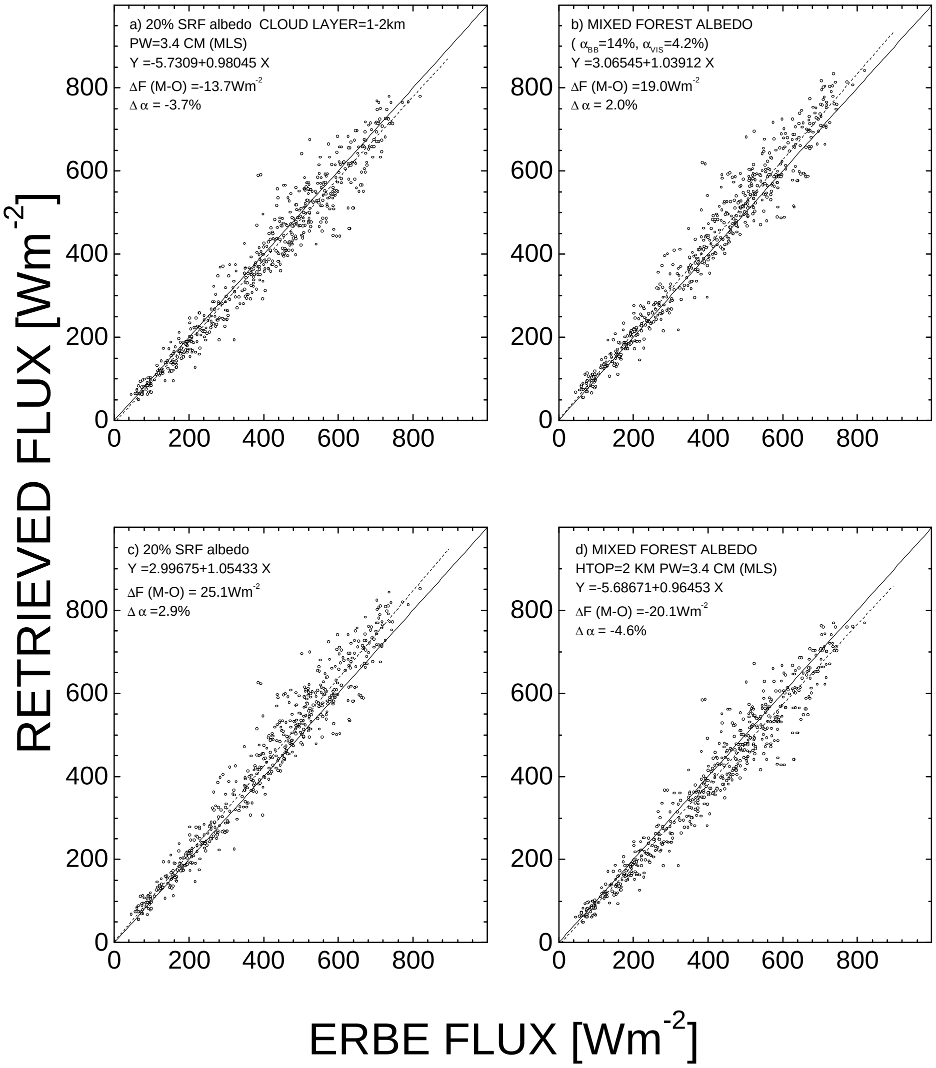

Figure 3. Comparison between ERBE TOA fluxes and fluxes retrieved from the surface observations. a)-d) panel correspond to different assumptions for surface and atmosphere properties.

observed shortwave (SW) fluxes under different surface, atmospheric, and cloud conditions in light of the lack of accurate knowledge on these variables. These comparisons are for Canadian data. Given the level of uncertainties, the agreements are considered to be fairly well. A further insight into the comparison reveals no apparent dependence on SZA and observation location. Figure 4 shows similar comparisons for ScaRaB over 22 stations and for CERES over 6 stations around the globe. The agreements in both comparisons are good, in particular for low flux values that correspond either to thick clouds or relatively large SZAs. The relatively large scattering for intermediate values indicates that it has something to do with cloud inhomogeneity, which renders erroneous match between satellite and surface. Moreover, for relatively thin clouds, influence of surface becomes more important and a specification of incorrect surface albedo could tarnish the comparison.

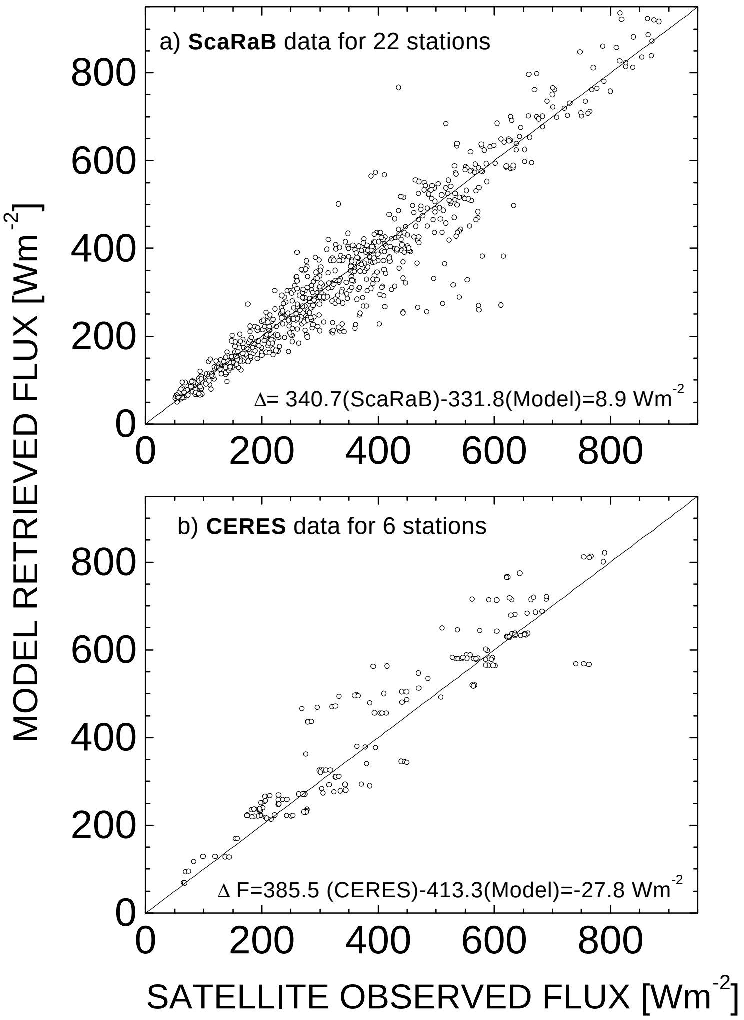

Figure 4. Comparison of ScaRaB and CERES fluxes with model retrieved values. Mixed forest surface albedo model, variable cloud top height, and precipitable water vapor (PWV) were used in retrievals.

Summary

This study first retrieved cloud optical depth from ground-based measurements from which TOA broadband fluxes are computed. The retrieved cloud optical depths are compared against ISCCP DX data, while the TOA broadband fluxes are compared with direct observations made by ERBE, ScaRaB, and CERES. All comparisons showed reasonable agreements. Minor differences are attributed to uncertainties in surface albedo, cloud layer location, and the column amount of atmospheric absorbers such as water vapor and aerosol, as well as to the effect of non-homogeneous clouds treated by the plane-parallel model.

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