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Cloud optical depths and TOA fluxes: Comparison between satellite and surface retrievals from multiple platforms

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Abstract. Performances of two cloud property retrieval schemes are assessed by comparison with each other. The study is limited to liquid phase clouds. Two parameters are assessed: cloud optical depth in the visible band and broadband shortwave (SW) flux at the top-of-atmosphere (TOA). Retrievals are based on look-up tables for a variety of conditions using an adding-doubling code coupled with LOWTRAN-7 transmittance models. Comparisons of cloud optical depths retrieved from ground measurements with those from ISCCP DX data agree better than previously reported comparisons with the original ISCCP CX data. Likewise, good agreement is obtained between retrieved and inferred TOA SW fluxes. Differences fall within uncertainties of input parameters, as well as shortcomings in the use of a plane-parallel radiative transfer model and in the inversion schemes themselves.

1. Introduction

Clouds play an essential role in the radiative processes that govern Earth's climate. An important property of cloud is optical depth τ. Much work has been done to retrieve both τ and other radiative variables using space-borne observations [*Rossow*, 1989]. Meanwhile, attempts were also made to retrieve τ using ground-based radiation measurements [*White et al.*, 1995; *Leontyeva and Stamnes*, 1996; *Barker et al.*, 1998]. It is worrisome to note that some studies showed considerable discrepancies between the values of τ resulting from the two approaches. For example, *Min and Harrison* [1996] applied their inversion algorithms to ground-based spectral transmittances observed during the Atmospheric Radiation Measurement (ARM) Program Intensive Observation Period (IOP). Their values were systematically larger than those retrieved from GOES-7. After modifying the calibration of GOES-7 data, *Dong et al.* [1998] reassessed the satellite retrieval following a similar approach but with broadband surface radiation data and found good agreement with retrievals based on GOES-7, but still poor for GOES-8. Some discrepancy has also been reported for cloud optical depths retrieved by different techniques from surface and satellite observations over the Antarctic coast [*Ricchiazzi et al.*, 1995; *Rossow and Schiffer*, 1999].

Barker et al. [1998] retrieved cloud optical depths for 21 stations across Canada using 20 years of ground pyranometer data. They compared their retrievals to those from the International Satellite Cloud Climate Climatology (ISCCP) CX data set at two stations and reported systematic differences similar to those found by *Min and Harrison* [1996]. New D-series ISCCP products differ significantly from CX data due to the use of modified satellite calibration and cloud microphysical models. The intent of the present study is to assess whether the new DX products are superior to CX products by making use of ground and other satellite data. To constraint possible uncertainties in the analysis, this study focused on liquid water clouds.

Cloud optical depths were retrieved from high temporal resolution (1 to 5 minutes) ground-based insolation measurements made at many sites around the world. The retrieved values were then compared to the ISCCP DX data set. An alternate consistency check was carried out by substituting retrieved τ into a radiative transfer model and calculating TOA broadband fluxes. They were then compared with direct inferences made by the Earth Radiation Budget Experiment (ERBE) [*Barkstrom et al.*, 1989], Scanner for Radiation Budget (ScaRaB) [*Kandel et al.*, 1998], and Cloud and Earth's Radiative Energy System (CERES) [*Wielicki et al.*, 1996] flown on Tropical Rainfall Monitoring Mission (TRRM) space platform. This type of closure experiment tests the integrity of the solar radiative transfer model and the accuracy of cloud parameter retrievals.

2. Data and cloud scene selection

Ground-based radiation measurements were collected under various programs. They include the Canadian radiation networks operated by the Meteorological Service of Canada [*Barker et al.* 1998]; NOAA's SURFRAD network [*Augustine et al.* 2000]; WMO's Baseline Surface Radiation Network (BSRN) [*Ohmura et al.* 1998]; and DOE's Atmospheric Radiation Measurement (ARM) Program [*Michalsky et al.* 1999]. The general assessment of the accuracy of surface radiometric measurements shows that surface instruments produce satisfactory measurements typically within 5-10 Wm^{-2} when necessary precaution measures taken into account [*Michalsky* et al., 1999]. Nevertheless, the thermal offset problem may affect some types of radiometer measurements additionally by 5-10 Wm^{-2} that occur mainly under clear-sky conditions [*Bush et al.*, 2000, *Ji and Tsay*, 2000]. Description of instrumentation and measurement characterization are beyond the scope of this article, but may be found in some of the listed references. Site locations and periods of observation are listed in Table 1. The table also contains information on satellite data (ISCCP, ERBE, ScaRaB and CERES) that were co-located with these ground observations. ISCCP DX data were employed for 1993, ERBE data from 1988 to 1990, ScaRaB data for 1994-95, CERES data for 1998. All analyses were limited to snow-free

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Table 1. List of locations

No	Station Name	Operating Agencies	Latitude	Longitude	Period	Satellite Project
1	Port Hardy	AES, Canada	50.68°	232.63°	88-90; 93, 94-95	ERBE, ISCCP, ScaRaB
2	Stony Plains	AES, Canada	53.53°	245.99°	88-90; 93, 94-95	ERBE, ISCCP, ScaRaB
3	Outlook	AES, Canada	54.483	252.95°	94-95	ScaRaB
4	Winnipeg	AES, Canada	49.90°	262.77°	88-90; 93, 94-95	ERBE, ISCCP, ScaRaB
5	Thompson	AES, Canada	55.75°	262.133°	93, 94-95	ISCCP, ScaRaB
6	Resolute	AES, Canada	. 74.717°	265.017	93	ISCCP
7	Egbert	AES, Canada	44.233	280.217	88-90, 94-95	ERBE, ScaRaB
8	Dorval	AES, Canada	45.47°	286.25 °	88-90; 93, 94-95	ERBE, ISCCP, ScaRaB
9	Charlottetown	AES, Canada	46.25°	296.867°	93, 94-95	ISCCP, ScaRaB
10	Goose Bay	AES, Canada	53.30°	299.63°	88-90; 93, 94-95	ERBE, ISCCP, ScaRaB
11	ARM SGP CF,	DOE ARM	36.60°	262.52°	94-95, 98	ScaRaB, CERES
12	Bondville	SURFRAD, NOAA	40.1°	271.383°	98	CERES
13	Goodwin Creek	SURFRAD, NOAA	34.25°	270.133°	98	CERES
14	Florianopolis	BSRN, WMO	-27.467°	311.517°	94-95, 98	ScaRaB, CERES
15	Lindenberg	BSRN, WMO	52.22°	14.12°	94-95	ScaRaB
16	Payerne	BSRN, WMO	46.82°	6.93°	94-95	ScaRaB
17	Tateno	BSRN, WMO	36.05°	140.133°	98	CERES

scenes, as determined by satellite scene identification with surface type flagged as snow/ice-free. Solar zenith angle was constrained to be larger than 0.2.

To ensure that overcast scenes identified by satellite correspond to overcast conditions at the ground, additional tests were applied that utilize statistics of measured surface downward radiation. Comparison of surface retrievals from Canadian data and satellite ISCCP DX data were conducted when all DX data falling within 55km (~1^0x1^0 area) from a ground site are comprised of water clouds and surface direct flux transmittance was less than 0.025. This small positive threshold is necessary because direct flux is computed as the difference between global and diffuse pyranometer measurements, both of which contain instrumental noise. Effectively, the condition led to an average direct flux less than 5.2 Wm^{-2}, thus ensuring a selection of overly cloudy scenes. Surface retrieved optical depths were compared to each DX pixel within ± 15-minute of satellite overpass. Optical depths were retrieved from surface flux data and averaged over 5-minute intervals.

When comparing TOA broadband fluxes, the selection criteria are somewhat different due to the coarser resolution of broadband satellite data. In addition to the tests described above, the following criteria are added: 30-minute standard deviations are less than 5 Wm^{-2} for direct flux, and less than 20 Wm^{-2} for diffuse component. 30-minute average surface fluxes were employed in the retrieval of cloud optical depths that were used to compute TOA broadband fluxes for comparison with broadband satellite measurements. The surface retrievals were compared to each individual satellite pixel within a 75-km area for ScaRaB, 50-km area for ERBE and 30-km area for CERES. These areas are proportional to satellite spatial resolution, which is 60 km for ScaRaB, 40 km for ERBE and 20 km for CERES at nadir point.

3. Retrieval scheme

The retrieval method utilizes lookup tables obtained by running an adding-doubling algorithm combined with LOWTRAN-7 atmospheric transmittance model with 105 spectral bands from 0.2 to 5.0 μm [*Masuda et al.*, 1995; *Kneizys* et al., 1987]. 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. Solar zenith angle was set to 5.90°, 13.52°, 21.12°, 28.63°, 36.01°, 43.20°, 50.15°, 56.80°, 63.10°, 68.95°, 74.28 °, 78.99 °, 82.98 °, 86.15 °, 88.41 ° and 89.70 °. Different surface albedo models were incorporated including those for evergreen forest, mixed forest surface type, and Lambertian surfaces with varying broadband albedos [*Rutan and Charlock*, 1997]. Spherical cloud particles were assumed with an effective radius of 7 μm for water droplets. Mie theory was applied to calculate the single scattering properties. The retrieval of τ from downwelling irradiance at the surface depends weakly on cloud particle size [*Leontyeva and Stamnes*, 1996; *Li et al.* 1999]. The look-up tables were created for 5 different standard atmospheric models [*Kneizys et al.* 1987]. A continental aerosol model with optical depth 0.1 was used for all atmospheres. Column water vapor amount was obtained for each set of measurements from the NCAR/NCEP REANALYSIS data set [*Kalnay et al*, 1996] with a 6-hour temporal resolution. Clouds were placed between 1 and 2 km above the ground level. Only scenes with clouds marked by ISCCP processing scheme as liquid clouds were selected for comparison with DX data. To discriminate between water and ice clouds for broadband comparison we estimated cloud top temperature using either brightness temperature in IR channel of ScaRaB radiometer or temperature derived from longwave (LW) flux observations of ERBE and CERES radiometers. LW flux was related to brightness temperature T_B through the following empirical expression

$$T_B = 139.2 + 0.696\,LW - 5.86\times10^{-4}\,LW^2 \qquad (1)$$

where T_B in [K], LW flux in [Wm^{-2}]. The relationship was derived from ScaRaB data. Clouds with T_B >255K were assumed to be liquid. In view of cloud emissivity and small atmospheric absorption above the cloud layer, this threshold approximately corresponds to ISCCP cloud top temperature 260K that was used to separate water and ice clouds. Multi-dimensional interpolation was done to determine τ and TOA broadband flux/albedo from surface transmittance, solar zenith angle and precipitable water. The interpolation was logarithmic for τ, quadratic for precipitable water and linear for cosine of solar zenith angle. The resulting TOA albedo estimates are compared with broadband satellite measurements.

4. Analysis of satellite and surface retrievals

Figure 1 shows a comparison of τ retrieved from ground measurements made in Canada and from ISCCP DX data. Retrievals were carried out with surface albedo corresponding to mixed forest model. Unlike the systematic discrepancy between surface retrievals and the CX data as found by *Barker et al.* [1998], Figure 1 shows that comparison with DX retrievals is in much better agreement. Average values of τ are 32.3 from ground retrievals and 26.6 from ISCCP DX. Although the difference in τ seems still sizable (~18%), its radiative effect is rather small (on average ~3%) due to a nonlinear response of flux to τ. In comparison, the values of cloud optical depth from ISCCP CX are much smaller than the ground-based estimates, a factor of 1.25~2.25 and average bias ~60% [*Barker et al.*, 1998]. Moreover, the frequency distributions obtained from ISCCP DX and ground observations with respect to cloud optical depth are very similar too, as is shown in Figure 2. The relatively large scatter in Fig. 1 stems most likely from spatial mismatch between surface and satellite observations. Uncertainties in cloud vertical structure may also contribute to the scattering. Note that the nominal resolution of ISCCP DX data is 30 km, but they actually represent a 4 km sample; an AVHRR GAC footprint located inside the 30-km grid without precise knowledge of location. Moreover DX data were selected from an area ~ $1^0 x 1^0$. This means that the satellite and surface-based retrievals of τ likely correspond to somewhat different cloud scenes, though their statistical distributions seem to be consistent with each other.

Figure 3 presents comparisons between model computed and ERBE-observed SW fluxes. These comparisons employed satellite data from all three ERBE-satellites and Canadian ground data. Linear regression is plotted as a dashed line together with the 1:1 line. The mean satellite observed flux is 513.8 Wm^{-2}, while the mean difference (model-satellite observation) is merely 0.5 Wm^{-2}. Standard deviation of flux difference is 55.6 Wm^{-2} or 10.8% of average observed flux. To evaluate the sensitivity of the retrievals to uncertainties in input factors, different surface albedo models were employed with a broadband albedo ranging from 12.6% to 20%, and visible albedo from 4.2% to 20%. Retrievals with fixed amount of water vapor corresponding to mid-latitude summer (MLS) were also carried out. The range of retrieved TOA fluxes is typically less than 10 Wm^{-2} (~2%). For example, the MLS atmosphere is more humid (3.4 cm) than average precipitable water amount for our data set (2.8 cm). As a result, model retrievals of TOA reflected fluxes employing the MLS atmosphere are smaller by 6.1 Wm^{-2} on average because of additional absorption by water vapor. An increase in surface broadband albedo from 12.6% to 20% resulted in an increase of TOA flux by 6.2 Wm^{-2}. This is about 10% of the standard deviation of flux difference (55.6 Wm^{-2}) as shown in Figure 3. There is essentially no dependence on solar zenith angle and observation location.

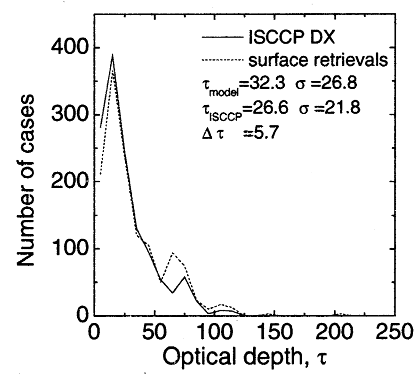

Figure 2. A comparison of the frequency distributions in water cloud optical depths retrieved from ISCCP-DX and surface irradiance measurements.

Figure 4 shows similar comparisons for ScaRaB over 13 stations and for CERES over 5 stations around the globe. Note, there are horizontal alignments for some points, which is caused by the selection of several satellite pixels within the qualified area of a surface station, so that one surface measurement may correspond to several satellite measurements. This is especially evident for CERES data. Absolute differences between mean model retrieved and satellite observed fluxes are also very small: –4.5 Wm^{-2} for ScaRaB and 2.1 Wm^{-2} for CERES. Standard deviations of the flux differences are 54.9 Wm^{-2} (11%) and 42.5 Wm^{-2} (7%) respectively. Statistical t-test was conducted to determine the significance of the hypothesis about identical mean values of datasets of retrieved and observed fluxes. For the data shown in Figures 3, 4a-b the t-values ranged between -0.233 and 0.099. This corresponds to the level of significance between 0.82 and 0.96, implying high probabilities of zero bias between modeled and observed TOA fluxes. The agreements are particularly good for low flux values corresponding either to thin clouds or relatively large solar zenith angles. The relatively large scattering for intermediate values indicates that it has more to do with cloud inhomogeneity, which renders more erroneous match between satellite and surface observations.

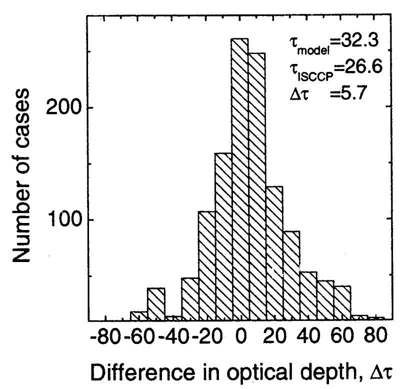

Figure 1. Histogram of the differences between ISCCP DX and ground-based retrievals of cloud optical depth for water clouds and Canadian data.

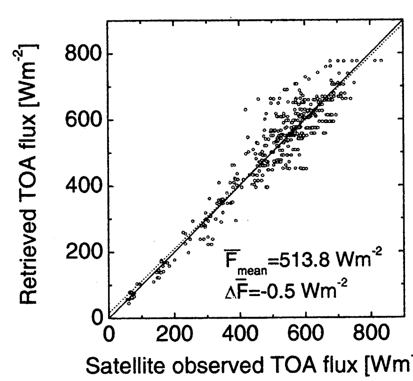

Figure 3. Comparison between TOA fluxes measured by ERBE and retrieved from surface irradiance observations. Mixed forest surface albedo model and variable precipitable water were used in retrievals.

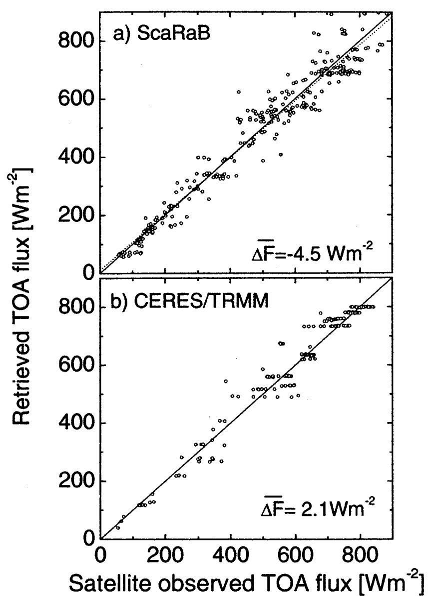

Figure 4. Comparison of ScaRaB and CERES fluxes with model retrieved values.

Satellite scene identification and the angular models employed for converting radiance to flux may also contribute to the discrepancies [*Wielicki et al.*, 1996; *Chang et al.*, 2000]. Moreover, for relatively thin clouds, influence of surface becomes more important and a specification of incorrect surface albedo could hamper the comparison.

5. Summary

Employing ground-based measurements and look-up tables computed from a radiative transfer model, cloud optical depths τ and TOA broadband fluxes were derived for liquid water clouds. The retrieved τ were compared with ISCCP DX data, while the TOA broadband fluxes were compared with ERBE, ScaRaB and CERES/TRMM observations. All comparisons showed agreements that fall well within the ranges of uncertainties in input data. Average values of τ were found to be 32.3 for ground retrievals and 26.6 for ISCCP DX data. The difference $\Delta\tau$=5.7 is much smaller than the discrepancy of a factor of 1.25-2.5 with ISCCP-CX data as reported before. Mean differences between ground retrieved and satellite inferred TOA broadband fluxes from ERBE, ScaRaB and CERES are only 2% with scattering up to 11%. Causes for the differences may be associated with uncertainties in specifications of surface albedo, cloud location, atmospheric model, radiance-to-flux conversion in satellite data processing and the effect of non-homogeneous clouds.

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References

Augustine J. A., J. J. DeLuisi, C. N. Long, SURFRAD – A national surface radiation budget network for atmospheric research. *Bull. Amer. Meteorol. Soc.*, **81**, 2341-2357, 2000

Barker, H.W, T. J. Curtis, E. Leontieva, K. Stamnes, Optical depth of overcast cloud across Canada: Estimates based on surface pyranometer and satellite measurements. *J. Climate*, 11, 2980-2994, 1998.

Barkstrom, B. R., E.F. Harrison, G. L. Smith, R. Green, J. Kibler, R. Cess, and the ERBE Science team, Earth Radiation Experiment (ERBE) archival and April 1985 results. *Bull. Amer. Meteor. Soc.*, 70, 1254-1262, 1989.

Bush, B. C., F. P. J. Valero, A. S. Simpson, and L. Bignone, Characterisation of thermal effect in pyranometers: A data correction algorithms for improved measurements of surface insulation, *J. Atmos. Ocean. Tech.*, 17, 165-175, 2000

Chang, F.-L., Z. Li, A. P. Trishchenko, The dependence of TOA reflectance anisotropy on cloud properties inferred from ScaRaB satellite data. *J. Appl. Meterol.* 39, 2480-2493, 2000.

Dong, X., W. L. Smith, Jr., P. Minnis, Comparison of stratus cloud optical depths retrieved from surface and GOES measurements over the ARM SGP central facility, *Proc. 8-th Atmospheric Radiation Measurement (ARM) Science Team Meeting.* March 1998, Tucson, USA, 207-213pp., 1998.

Ji, Q., and S.-C. Tsay, On the dome effect of Eppley pyrgeometers and pyranometers, *Goeophy. Res. Let.*, 27, 971-974, 2000.

Kalnay, E., and Coauthors, The NCEP/NCAR 40-year reanalysis project. *Bull. Amer.Meteor.Soc.*, 77, 437-471, 1996.

Kandel, R., and Coauthors, The ScaRaB Earth radiation budget dataset. *Bull. Amer. Meteor. Soc.*, 79, 765-783, 1998

Kneizys, F.X., E. P. Shettle, L.W. Abreau, J. Chetwynd, G. Anderson, W. Gallery, J. Selby, and S. Clough, 1988: *User's Guide to LOWTRAN-7, AFGL-TR-88-0177.* 140pp. [Available from AFGL (OPI), Hanscom, AFB, MA, USA.]

Leontieva, E., and Stamness, K., Remote sensing of cloud optical properties from ground-based measurements of transmittance: A feasibility study. *J. Appl. Meteor.*,35, 2011-2022, 1996.

Li, Z., A. Trishchenko, H.W. Barker, G. L. Stephens, P. T. Partain, Analysis of Atmospheric Radiation Measurement (ARM) program's ARESE multiple data sets for studying cloud absorption, *J. Geophys. Res.* 104, 19127-19134, 1999.

Masuda, K., H. G. Leighton, and Z. Li, A new parameterization for the determination of solar flux absorbed at the surface from satellite measurements. *J. Climate,* 8, 1615-1629, 1995.

Michalsky, J., E. Dutton, M. Rubes, D. Nelson, T. Stoffel, M. Wesley, M. Splitt, J. DeLuisi, Optimal measurement of surface shortwave irradiance using current instrumentation, *J. Atmos. Ocean. Tech.*, 16, 55-69, 1999.

Min, Q. and L.C. Harrison, Cloud properties derived from surface MFRSR measurements and comparison with GOES results at the ARM SGP site. *Geophys. Res. Lett.*, 23, 1641-1644, 1996.

Ohmura A., and Coauthors, Baseline Surface Radiation Network (BSRN/WRMC): New precision radiometry for climate research, *Bull. Amer. Meteor. Soc.*, 79, 2115-2136, 1998.

Ricchiazzi, P., C. Gauthier, and D. Lubin, Cloud scattering optical depth and local surface albedo in the Antarctic: Simultaneous retrieval using ground based radiometry. *J.Geophys. Res.*, 100, 21 091-21 104, 1995.

Rossow, W. B., and R. A. Schiffer. Advances in understanding clouds from ISCCP. *Bull. Amer. Meteor. Soc.*, 80, 2261-2287, 1999.

Rossow, W.B., Measuring cloud properties from space: A review. *J. Climate*, 2, 201-213, 1989.

Rutan, D., and T. P. Charlock, Spectral reflectance, directional reflectance, and broad-band albedo of the earth's surface. *Proc. 9th Conf. Atmos. Radiation*, Long Beach, California, pp. 466-470, 1997.

White, A. B., C. W. Fairall, J. B. Snider, Surface-based remote sensing of marine boundary layer cloud properties. *J. Atmos. Sci.*, 52, 2827-2838, 1995.

Wielicki, B. A., and Coauthors, Clouds and the Earth's Radiant Energy System (CERES): an Earth Observing System experiment. *Bull. Amer. Meteor. Soc.*, 77, 853-868, 1996.

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