

## Apparent absorption of solar spectral irradiance in heterogeneous ice clouds

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[1] Coordinated flight legs of two aircraft above and below extended ice clouds played an important role in the Tropical Composition, Cloud and Climate Coupling Experiment (Costa Rica, 2007). The Solar Spectral Flux Radiometer measured up- and downward irradiance on the high-altitude (ER-2) and the low-altitude (DC-8) aircraft, which allowed deriving apparent absorption on a point-by-point basis along the flight track. Apparent absorption is the vertical divergence of irradiance, calculated from the difference of net flux at the top and bottom of a cloud. While this is the only practical method of deriving absorption from aircraft radiation measurements, it differs from true absorption when horizontal flux divergence is nonzero. Differences between true and apparent absorption are inevitable in any inhomogeneous atmosphere, especially clouds. We show, for the first time, the spectral shape of measured apparent absorption and compare with results from a three-dimensional radiative transfer model. The model cloud field is created from optical thickness and effective radius retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator and from reflectivity profiles from the Cloud Radar System, both on board the ER-2. Although the spectral shape is reproduced by the model calculations, the measured apparent absorption in the visible spectral range is higher than the model results along extended parts of the flight leg. This is possibly due to a net loss of photons into neighboring cirrus-free areas that are not contained within the model domain.

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### 1. Introduction

[2] The issue of real versus apparent absorption of solar radiation within clouds was discussed for decades after *Fritz and MacDonald* [1951] discovered that cloud absorption derived from measurements may far exceed model results. Despite its significance for atmospheric energy budget assessments, cloud dynamics, and remote sensing, a conclusive explanation for this persistent bias is still lacking. At best, a

status quo was achieved; some authors argued that the problem is ill-posed because the measurement (or model) errors are too large for a final assessment of the bias, others found model-measurement agreement within the given uncertainties. *Stephens and Tsay* [1990] reviewed the observational evidence for various manifestations of the effect and summarized explanations for the discrepancies. Thereafter, a controversial discussion was initiated by new observations [*Cess et al.*, 1995; *Ramanathan et al.*, 1995; *Pilewskie and Valero*, 1995]. For a range of conditions, follow-up studies either rejected [*Hayasaka et al.*, 1995; *Arking*, 1996; *Stephens*, 1996; *Taylor et al.*, 1996; *Francis et al.*, 1997; *Ackerman et al.*, 2003] or supported [*Pilewskie and Valero*, 1996, *Valero et al.*, 1997, 2000; *Zhang et al.*, 1997; *O'Hirok et al.*, 2000; *O'Hirok and Gautier*, 2003] the existence of a bias. Many studies favored horizontal photon transport in heterogeneous clouds as the cause of the discrepancies [*Newiger and Baehnke*, 1981; *Ackerman and Cox*, 1981; *Rawlins*, 1989; *Titov*, 1998; *Marshak et al.*, 1997, 1998, 1999; *Harshvardhan et al.*, 1998]. Other explanations were also suggested such as enhanced in-cloud water vapor absorption [e.g., *Francis et al.*, 1997; *Arking*, 1999], large drop contributions [*Wiscombe et al.*, 1984; *Ackerman and Stephens*, 1987; *Knyazikhin et al.*,

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2002], and in-cloud aerosols [Newiger and Baehnke, 1981; Chýlek et al., 1984, 1996; Wendisch and Keil, 1999].

[3] Certainly, discrepancies may be caused by a combination of multiple effects, all of which can be ascribed to inappropriate model assumptions or insufficient observations. Adequate spectral resolution in models and measurements is essential for separating the roles of gas and condensed species and for attributing biases to causes. For example, absorption by water vapor, aerosol, liquid water or ice can be distinguished by spectral signatures, whether or not the absorption is enhanced due to photon path lengthening in heterogeneous clouds. Prior to the late 1990s, most experiments did not make use of spectrally resolved measurements. Instruments with full spectral coverage over the solar wavelength range were introduced by Pilewskie et al. [2003] and Wendisch et al. [2001] for use in aircraft experiments. Despite this important advancement in measurement technology, aspects of the absorption bias problem lingered for a number of reasons: In typical experiments, absorbed irradiance is derived by subtracting net irradiance (difference of downward and upward irradiance) at cloud base and cloud top. This introduces large systematic errors in estimates of cloud absorption because it is the (small) difference of four large quantities. If the measurements above and below clouds are not coordinated in time and space, cloud heterogeneities add further uncertainty. Even if they are coordinated, the measurements may be affected by a net transport of photons through the sides of the sampling volume (net horizontal photon outflux or influx). Horizontal irradiance divergence (convergence) is balanced by the vertical flux divergence which can be misinterpreted as true absorption. We refer to vertical flux divergence as apparent absorption, different from true absorption by the magnitude of horizontal flux divergence.

[4] Horizontal photon transport can be understood in the context of radiative smoothing. Over some scale, contrasts in cloud optical thickness are smoothed out in the corresponding reflectance and transmittance fields [Marshak et al., 1995]. For cloud fields with shadow effects (i.e., clouds with pronounced vertical structure) a roughening can occur as well [Marshak et al., 2006]. For the case of smoothing, the horizontal displacement of a photon relative to its entrance into a cloud field is determined by the number of scatterings it undergoes and by the asymmetry parameter. Platnick [2001] shows that this characteristic distance is a function of wavelength. In the absence of shadows and sources, the horizontal redistribution of photons in a smoothing process as seen from space (reflectance) can be viewed as transport from optically thick to optically thin regions within the characteristic smoothing scale. The photon path length distribution associated with these processes can be fundamentally different for optically thick regions (diffusion regime) and thin, sparsely populated areas [Davis and Marshak, 2001].

[5] Various methods were proposed to correct for horizontal flux divergence in aircraft measurements of absorption. Ackerman and Cox [1981] introduced a technique for sampling radiation with a combination of broadband and filter radiometers. Absorption measurements were corrected under the assumption that clouds do not absorb in the visible wavelength range and that radiative smoothing affects non-absorbing and absorbing wavelengths equally. Marshak et al. [1999] suggested various correction schemes. One of these

explicitly takes into account a predetermined radiative smoothing scale. Although this improves the Ackerman and Cox method considerably, it does not entirely reproduce the true absorption. Titov [1998] (among others) suggested averaging of cloud absorption measurements over the entire flight leg and provided minimum domain sizes based on typical boundary layer clouds.

[6] In this paper, we pursue a different strategy. Since true absorption is difficult to derive from measurements, we focus on apparent absorption, as obtained from two-aircraft observations, and we reproduce measured apparent spectral absorption (vertical flux divergence) on a pixel-by-pixel basis with 3-D radiative transfer (RT) calculations. This strategy is akin to that used by O'Hirok and Gautier [2003] who employed ground-based cloud observations as input to 3-D RT calculations. We used airborne measurements from the NASA Tropical Composition, Cloud and Climate Coupling Experiment (TC<sup>4</sup>, Costa Rica, 2007) [Toon et al., 2010]. An extensive set of instruments was deployed on board two aircraft, the NASA ER-2 and DC-8. The Solar Spectral Flux Radiometer (SSFR [Pilewskie et al., 2003]) was flown on both platforms and measured spectrally resolved upward and downward solar irradiance. The ER-2 carried the MODIS (Moderate Resolution Imaging Spectroradiometer) Airborne Simulator (MAS [King et al., 1996]), the Cloud Radar System (CRS [Li et al., 2004]), and other remote sensing instruments. It was operated at 20 km altitude – well above cloud-top level. The DC-8 was flown within and below cloud layers and was equipped with instrumentation for cloud microphysical, aerosol particle, and gas-phase measurements. On seven flight days, the ER-2 and DC-8 were closely coordinated (in space and time) along several flight legs (typically about a half an hour duration per leg) that were chosen in outflow regions near tropical cloud convective cells. In this way, detailed cloud structure data were acquired along with simultaneous above- and below-cloud measurements of solar spectral irradiance. Measurements of cloud-reflected radiance were used for the retrieval of cloud optical thickness and particle size.

[7] We determined point-by-point apparent spectral absorption for one case and compared with model results. The calculated irradiance fields were obtained from 3-D RT calculations, using measurements from MAS and CRS to derive the input cloud field.

[8] The paper starts with a brief description of the instruments, measurement strategy, data processing, generation of the 3-D cloud, and of the 3-D RT model (section 2). Results are presented in section 3. In the conclusions (section 4), possible implications for remote sensing and atmospheric energy budget are discussed.

## 2. Instruments, Data, and Radiative Transfer Calculations

### 2.1. Solar Spectral Flux Radiometer

[9] The SSFR [Pilewskie et al., 2003] measured spectral shortwave irradiance on the ER-2 (above clouds) and on the DC-8 below or within clouds. On both platforms, the up- and down-looking optical inlets were fix-mounted on the aircraft fuselage and connected to rack-mounted spectrometers through optical fibers. The spectral range (350–2150 nm) was covered by using two spectrometers per optical inlet: a grating

spectrometer with a Silicon charge-coupled device array for near-ultraviolet (NUV), visible (VIS), and very near infrared (350–1000 nm, 8 nm spectral resolution) and a spectrometer with indium-gallium-arsenide linear array detector for the shortwave infrared (900–2200 nm, 12 nm resolution) wavelength range. Over the entire range, about 90% of the solar irradiance spectrum is captured. The slit functions and wavelength response of the spectrometers were measured in the laboratory prior to the field experiment. An absolute radiometric calibration with a National Institute of Standards and Technology (NIST) traceable light source (1000 W lamp) was performed in the laboratory before and after the experiment. The stability of the calibration was monitored with field calibrators throughout the experiment. The absolute radiometric accuracy was 3%–5% (precision 0.1%). The data were corrected for the angular response of the light collectors and for changes in downward irradiance due to aircraft attitude. The attitude correction was necessary because the light collector reference plane (SSFR horizon) deviated from horizontal alignment due to changes in aircraft pitch, roll, and heading; active stabilization as described by *Wendisch et al.* [2001] was not available for this experiment. In some cases, the attitude correction failed because of reflections from nearby clouds that could not be accounted for by the correction algorithm.

## 2.2. Deriving Cloud Absorption From SSFR Measurements

[10] In aircraft measurements, cloud absorption is derived from the difference of net irradiance,  $F_{\text{net}} = F^{\downarrow} - F^{\uparrow}$ , at the top and bottom of a layer:  $\Delta F_V = F_{\text{net,top}} - F_{\text{net,bot}}$ , where  $\Delta F_V$  denotes the vertical component of flux divergence (vertical difference of net irradiance). It differs from true absorption ( $F_{\text{abs}} = \Delta F = \Delta F_V + \Delta F_H$ ) when horizontal flux divergence  $\Delta F_H \neq 0$ . Owing to net horizontal photon transport,  $\Delta F_H$  is nonzero for any inhomogeneous distribution of atmospheric extinction, particularly in heterogeneous clouds. In absence of physical absorbers,  $F_{\text{abs}} = 0$ , and  $\Delta F_H$  is balanced by  $\Delta F_V$  that is opposite in sign. The magnitude of  $\Delta F_V$  is a measure for net horizontal photon transport, and is called apparent absorption. For nonconservative scattering,  $\Delta F_V$  incorporates real absorption ( $F_{\text{abs}}$ ) and net horizontal transport effects:  $\Delta F_V = F_{\text{abs}} - \Delta F_H$ . For pronounced horizontal heterogeneity,  $\Delta F_H$  may dominate  $\Delta F_V$ , which makes it hard to estimate  $F_{\text{abs}}$ . We focus on  $\Delta F_V$  because no assumptions about cloud heterogeneity are necessary to derive it from the measurements, in contrast to  $F_{\text{abs}}$ .

[11] Fractional absorption (or apparent layer absorptance) is obtained from  $\Delta F_V$  by normalizing with  $F^{\downarrow}_{\text{top}}$ . While error analysis is virtually impossible when estimating  $F_{\text{abs}}$  from  $\Delta F_V$ , it is nontrivial to derive realistic error estimates even for  $\Delta F_V$  itself. A brute force method would be to combine the radiometric uncertainties (3%–5%) with linear error propagation:  $e(\Delta F_V) \approx |e(F^{\downarrow}_{\text{top}})| + |e(F^{\uparrow}_{\text{top}})| + |e(F^{\downarrow}_{\text{bot}})| + |e(F^{\uparrow}_{\text{bot}})|$ , where  $e$  denotes systematic absolute instrument uncertainties. However, since all spectrometers are calibrated with the same light source, the errors are not independent. A more realistic uncertainty estimate would be the stability of the spectrometer response functions throughout the experiment (better than 1%–2% during TC4). Another major contributor to total uncertainty is the horizontal misalignment of the sensors. Even after correcting for aircraft attitude, a

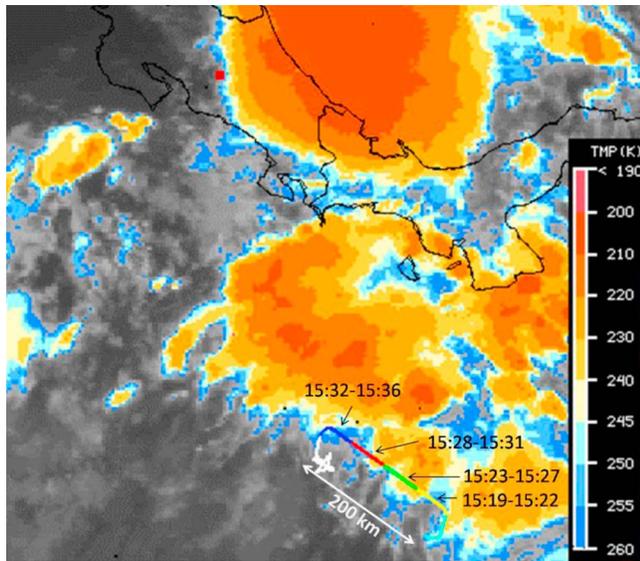
residual error remains. It can exceed radiometric uncertainty [*Wendisch et al.*, 2001] and is hard to derive from theoretical considerations as it depends on the specific measurement situation. We therefore used an empirical estimate of 7% for the maximum total error in downward irradiance. This error subsumes contributions from radiometric calibration, attitude correction, and angular response of the light collectors and was determined by comparing downward modeled and measured irradiance above clouds and in cloud-free areas for all wavelengths (excluding gas absorption bands). More detail for estimating the error due to changing aircraft attitude is given by *Schmidt et al.* [2010]. For the upward irradiance, we used 5% as maximum error estimate. The net irradiance error was obtained from linear error propagation:  $e(F_{\text{net,top}}) \approx |e(F^{\downarrow}_{\text{top}})| + |e(F^{\uparrow}_{\text{top}})|$  and  $e(F_{\text{net,bot}}) \approx |e(F^{\downarrow}_{\text{bot}})| + |e(F^{\uparrow}_{\text{bot}})|$ . The top-of-cloud and bottom-of-cloud errors were combined by Gaussian error propagation:  $e(\Delta F_V) \approx (e(F_{\text{net,top}})^2 + e(F_{\text{net,bot}})^2)^{1/2}$ .

## 2.3. MODIS Airborne Simulator

[12] The horizontal cloud structure was inferred from the MODIS Airborne Simulator (MAS [*King et al.*, 1996]). It provided fields of cloud-top height, optical thickness ( $\tau$ ) and effective cloud particle radius ( $r_{\text{eff}}$ ) at a resolution between 20 and 50 m (depending on flight altitude and cloud-top height). For high clouds, the cloud-top height retrieval was based on the CO<sub>2</sub> slicing technique as used by MODIS [*Menzel et al.*, 2008]. The algorithm that normally uses four CO<sub>2</sub> MODIS channels was adapted to use the three channels available on MAS. However, the actual MAS cloud-top properties retrieval obtains realistic solutions using two CO<sub>2</sub> channels only. For low clouds, the algorithm reverts to the IR window method. The retrieval of optical thickness and effective radius was based on the work of *Nakajima and King* [1990]: For each pixel, reflectance pairs in a visible (or shortwave infrared) channel and a near-infrared channel were compared with one-dimensional forward model calculations. While the shorter wavelength channel was chosen outside gas absorption bands and contains mainly information on optical thickness, the longer wavelength near-infrared channel is affected by liquid water or ice absorption and is sensitive to drop or crystal size. The closest match of the observed reflectance with precalculated modeled values was used to infer the optical thickness and effective radius pair. For the TC<sup>4</sup> data processing, algorithms similar to the ones used in MODIS collection 5 retrievals were used, where scattering phase functions and single scattering albedo for ice clouds rely on calculations by *Baum et al.* [2005]. Liquid water cloud scattering phase functions were derived from Mie calculations based on gamma drop size distributions with an effective variance of 0.1 [*Platnick et al.*, 2003]. Detailed instrument information and a description of the retrieval algorithm are given by *King et al.* [2004, 2010]. MAS data collected during TC<sup>4</sup> were compared with MODIS cloud retrievals [*King et al.*, 2010].

## 2.4. Cloud Radar System

[13] The vertical cloud structure below the ER-2 flight track was derived from the reflectivity profiles measured by the cloud radar system (CRS [*Li et al.*, 2004]) on board the ER-2. The resolutions of the reflectivity field are 37.5 m in the vertical and about 100 m in the horizontal. The minimum



**Figure 1.** ER-2 flight leg from 1519 to 1536 UTC, in the context of the GOES 10 and 12 IR image from 1528 UTC. The DC-8 was flown directly underneath. Image courtesy NASA Langley Research Center (<http://www-angler.larc.nasa.gov/tc4/>).

detectable reflectivity is about  $-28$  dBZ for CRS at a distance of 15 km. The reflectivity from CRS has been compared with the reflectivity from another radar at the X-band on the ER-2 near the cloud top. Near the cloud top, the reflectivities at both radar frequencies are about the same, an indication that the ice particles obey Rayleigh scattering [Tian *et al.*, 2010].

## 2.5. Case From 17 July 2007

[14] We selected one of the well-coordinated flight legs from 17 July 2007 (from 1520 to 1535 UTC). Figure 1 shows this flight leg in the larger-scale context GOES infrared image from 1528 UTC). It was located 300 km south of Panama (around  $5^{\circ}\text{N}$ ,  $83^{\circ}\text{W}$ ), near the edge of a high-cloud system. The concurrent GOES VIS image (not reproduced here) shows that the cirrus-free area was partly covered by low-level clouds. The Sun azimuth was northeast, at a zenith angle of approximately  $35^{\circ}$ .

[15] Both aircraft were guided from the mission operation center at the airport in San José using NASA’s Real Time Mission Monitor tool (RTMM; <http://rtmm.nsstc.nasa.gov/>) that allowed the mission manager to coordinate the aircraft within two minutes on exactly the same ground track. In the 17 July case, the ER-2 and DC-8 were less than twelve seconds apart on every point along the track. Despite the frequent occurrence of coordinated flight legs throughout the experiment, only one case qualified for our study based on stringent selection criteria: In order to correctly quantify cloud absorption, the bulk of the cloud layer had to be bracketed by the two aircraft. Owing to logistical constraints the DC-8 was frequently scheduled to fly only in cloud; that is, no below-cloud legs were scheduled. Even for the 17 July case studied here the DC-8 flew almost entirely within the cloud layer. Since no vertical structure was available from MAS, the information from CRS on board the ER-2 was vital in order to account for the position of the DC-8 within the cloud.

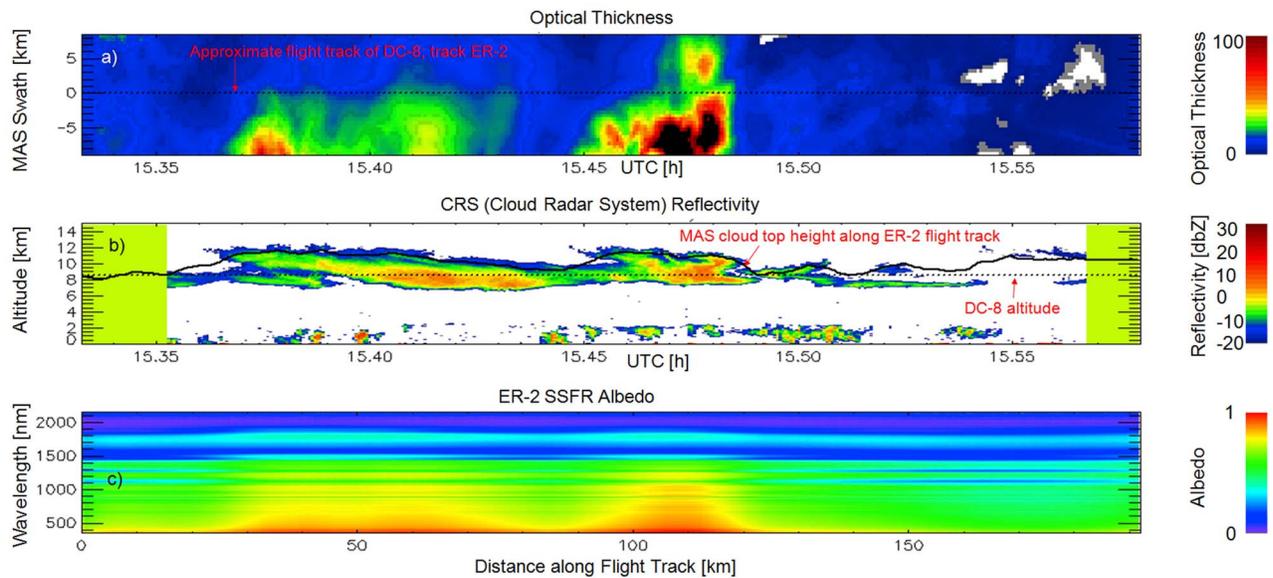
Without this information, it would be impossible to match measured and modeled irradiance at the position of the DC-8. A further, less stringent, requirement was that clouds be composed entirely of ice crystals, determined by the pixel-by-pixel thermodynamic phase information from MAS. Finally, only cases where the attitude correction could be applied (pitch and roll angles within certain limits) were used. These three requirements limited the amount of useable data considerably.

[16] Figure 2 shows the MAS-retrieved cloud optical thickness (gridded to 500 m resolution), CRS reflectivity, and the SSFR spectral albedo for the same ER-2 flight leg as in Figure 1. For the upper panel, blue colors correspond to low; red and black colors to high optical thickness. Cloud gaps are represented by white. The length of the scene is 198 km, the width (swath) 17.5 km. In Figure 2, the southeast to northwest flight track is aligned from left to right. The green shaded areas in the CRS panel mark areas where no data were available. The thick black line represents the MAS-derived cloud-top height along the ER-2 flight track, which captures the cloud-top structure rather well. The dotted line indicates the approximate flight altitude of the DC-8, showing that the aircraft was actually within rather than below cloud during large sections of the leg. In some areas, the radar sensed low-level clouds between the surface and 4 km altitude that were decoupled from the high-level outflow of the cell northeast of the flight leg. The bottom panel shows time series of spectral albedo, with the wavelength varying in the vertical. The SSFR albedo is nearly saturated in the visible wavelength range (red values indicating an albedo near unity) in the optically thick cloud regions. The albedo time series (horizontal lines in the albedo panel) exhibits far less variability than the associated cloud optical thickness, mainly due to the hemispherical (geometrical) averaging inherent to irradiance. Some of the wavelengths show minima that correspond to gas absorption bands. Ice absorption bands (for example around 1500 nm) can also be distinguished.

[17] Table 1 shows basic statistics of the cloud field. The upper three lines show mean, minimum, maximum and standard deviation of optical thickness, effective radius, and cloud-top height, as derived from MAS throughout the model domain. The uncertainties behind the mean values are derived from the level 2 products. They are discussed further by Kindel *et al.* [2010]. The lower three lines show the cloud-top altitude, bottom altitude, and geometrical thickness as derived from CRS along the nadir track of the ER-2 (only ice cloud portion above 6 km). For comparison, the cloud-top altitude along nadir as derived from MAS is also shown. The mean cloud-top height is 10.8 km (CRS), 10.7 km (MAS, domain average), and 10.3 km (MAS, nadir track average).

## 2.6. Input Cloud Generation

[18] The fields of optical thickness and effective radius from MAS and the reflectance data from CRS were combined to provide the input to 3-D radiative transfer calculations. The profile of radar reflectivity  $Z$  (in units of dBZ) was used to derive approximate vertical profiles of ice water content (IWC( $z$ ), in  $\text{g m}^{-3}$ ) along the flight track following Liu and Illingworth [2000]:  $\text{IWC} = 0.137 \times Z^{0.64}$ . For each vertical profile along the flight track, the column-integrated ice water path ( $\text{IWP}_{\text{CRS}}$ ) was calculated. The IWP was also retrieved from MAS:  $\text{IWP}_{\text{MAS}} = 2/3 \times \rho_{\text{ice}} \times \tau \times r_{\text{eff}}$ , where  $\rho_{\text{ice}}$  is the



**Figure 2.** Data along the 17 July flight track (1520–1535 UTC (UTC = 15.33h–UTC = 15.58h)). (a) MAS-retrieved cloud optical thickness (total swath width 17.5 km) as viewed from above; the dotted line indicates the tracks of the DC-8 and ER-2 in the middle of the MAS swath. (b) Radar reflectivity from CRS in dBZ (side view). Regions with no data available are marked in light green. Cloud-top height from MAS along the ER-2 flight track is overplotted as a bold line; the dotted line indicates the approximate flight altitude of the DC-8. (c) ER-2 SSFR albedo (wavelength vertical dimension) along the flight track.

density of ice (approximately  $0.925 \text{ g cm}^{-3}$ ). While the CRS profile was only measured along the center (nadir) track, MAS-derived IWP was available across the entire swath for each point along the track. In the model cloud, the IWC profiles were obtained through  $IWC(z) = IWC_{\text{CRS}} \times IWP_{\text{MAS}} / IWP_{\text{CRS}}$ . The resulting profile  $IWC(z)$  was shifted in altitude corresponding to the cloud-top height as retrieved by MAS. Due to the lack of other information, the effective radius was set to  $r_{\text{eff}}(x,y,z) = r_{\text{eff,MAS}}(x,y)$ , which is clearly a simplification because the crystal size distribution in the lower regions of the cloud is fundamentally different from that near the top. The MAS-derived effective radius is representative of the topmost layer of the cloud [Platnick, 2000] where ice crystals are often smaller than in lower layers within the cirrus [Francis et al., 1998; Gayet et al., 2004]. It should be noted that the MAS-retrieved optical thickness is conserved by the cloud generation method, and that the information from CRS is only used for the vertical distribution of extinction values throughout the column. The CRS profiles (available only along the ER-2 flight track) were used across the entire MAS swath. Since scattering at nonabsorbing wavelengths is primarily determined by the 3-D distribution of cloud extinction, the simplification of a vertically constant effective radius is justified in these cases. For absorbing wavelengths, measurement-model discrepancies are possible because absorption is a function of optical thickness and effective radius. However, a considerable part of radiation is absorbed in the uppermost cloud layer. Therefore, the cloud-top effective radius can be regarded as a valid representation for our study.

[19] The generated 3-D cloud was gridded to 0.5 km horizontal and 1.0 km vertical resolution. The impact of spatial resolution is not the focus of this particular study; for testing, a version with 0.1 km horizontal resolutions was also gen-

erated. Radiative transfer model runs at 500 nm wavelength showed that the irradiances were hardly affected by the increased horizontal resolution. The high-resolution cloud was therefore excluded from further analysis, in the interest of saving CPU time. The vertical resolution of 1.0 km was chosen larger than the mismatch between CRS- and MAS-derived cloud-top altitude (0.5 km; see Table 1).

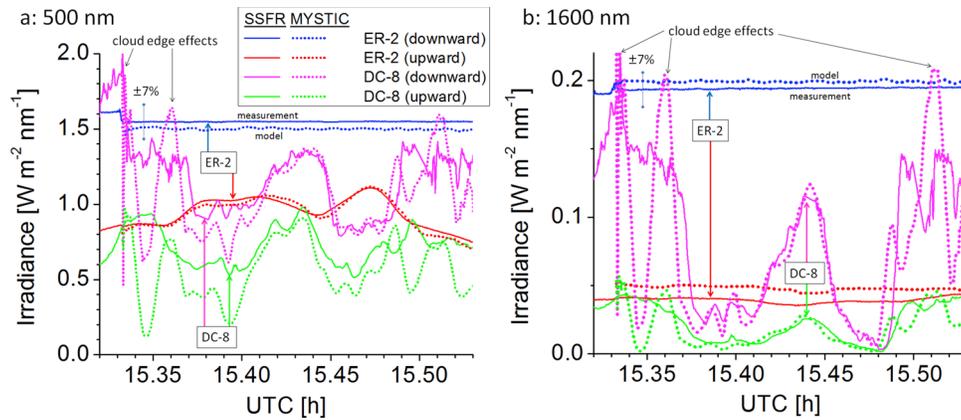
## 2.7. Radiative Transfer Calculations

[20] All calculations were done with the libRadtran radiative transfer package developed by Mayer and Kylling [2005]. The generated cloud microphysical properties within the  $384 \times 35 \times 20$  boxes ( $n_x \times n_y \times$  number of layers) constitute the main input for 3-D RT calculations, along with atmospheric profiles from dropsondes (launched from the DC-8), and from the DC-8 and ER-2 meteorological data (pressure, relative humidity). For the spectral sea surface albedo, data measured by SSFR during CRYSTAL-FACE (Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida

**Table 1.** Statistical Properties of the Cloud Measured on 17 July 2007 From MAS (Domain Average or Track Average) and CRS (Track Average)

	Mean	SD	Minimum	Maximum
Optical thickness, domain	$12.5 \pm 2.5^a$	$5.5^a$	3.5	100.0
Effective radius, domain ( $\mu\text{m}$ )	$27.5 \pm 2.8^a$	$4.6^a$	4.1	42.8
Cloud-top MAS (km)				
Domain	10.7	0.8	8.2	12.6
Track	10.3	0.9	8.4	11.8
Cloud-top CRS, track (km)	10.8	1.3	7.6	12.6
Cloud-bottom CRS, track (km)	7.5	1.0	6.5	11.5
Geometrical thickness CRS (km)	3.3	1.5	0.0	5.6

<sup>a</sup>Discussed by Kindel et al. [2010].



**Figure 3.** Time series of downward and upward irradiance, (a) 500 nm and (b) 1600 nm, measured on board the DC-8 and ER-2 (solid lines), along with the 3-D model results (dotted lines).

Area Cirrus Experiment) were used [Schmidt *et al.*, 2007b]. For the 3-D RT calculations, we applied the forward version of the Monte Carlo code MYSTIC (Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres [Mayer, 1999, 2009]) that is embedded in libRadtran (<http://www.libradtran.org>). The extraterrestrial spectrum by Kurucz [1992], averaged over 1 nm bins, was used as top-of-the-atmosphere incident solar irradiance spectrum. For the sake of computational efficiency, the scattering phase functions were represented by the Henyey-Greenstein parameterization based on the asymmetry parameter  $g$  (the first moment of the phase function). For irradiances, this approximation is reasonably close to the exact representation of the cloud phase function, at least for sun angles not too far from zenith position [Schmidt *et al.*, 2007b]. Both asymmetry parameter and single scattering albedo were taken from ray tracing calculations by Yang and Liou [1998]. Calculations were performed for nine wavelengths: 400, 450, 500, 600, 700, 800, 850, 1200, and 1600 nm, using  $10^9$  photons each. Periodic boundary conditions were used, to ensure energy conservation in the model.

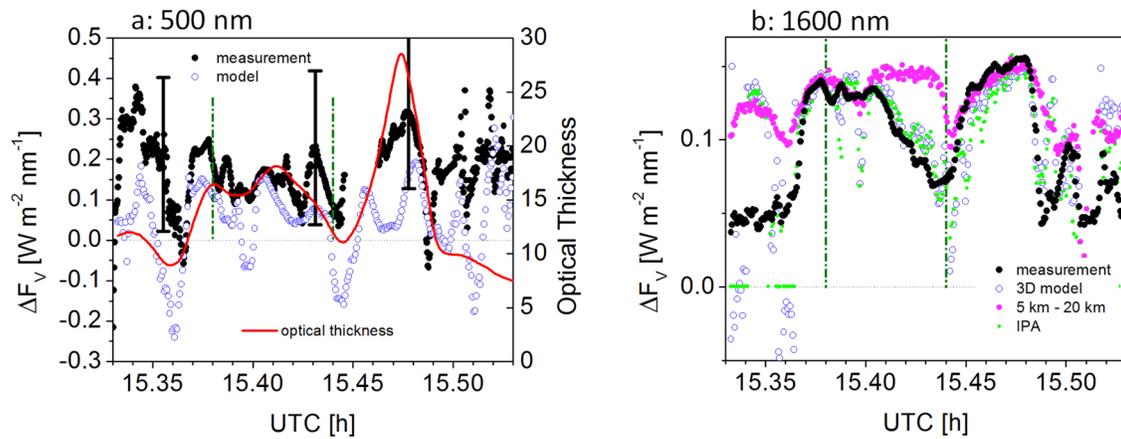
### 3. Results

[21] As a first step, we compared the measured time series of upward and downward irradiance above (that is, at ER-2 altitude) and below (or within) clouds (that is, at DC-8 altitude) with model results. To this end, the downward irradiance was rescaled such that changes in solar zenith angle (ranging from  $SZA = 34^\circ$ – $36^\circ$  during the leg) were compensated using  $F^\downarrow(SZA_0) = F^\downarrow(SZA) \times (\cos(SZA_0)/\cos(SZA))$ , where  $SZA_0 = 35^\circ$  was used in the model calculations as well. This correction is discussed by Schmidt *et al.* [2007a].

[22] Figure 3 shows the measurements and model results at DC-8 and ER-2 altitude for (1) 500 nm (non-absorbing wavelength) and (2) 1600 nm (absorbing wavelength). The variability of the modeled downward irradiance above clouds (blue dotted lines) reflects statistical (photon) noise; the variability of the measurements is due to the residual error after the attitude correction, discussed in section 2. For example, the ER-2 turned at about 15.33 h (1520 UTC), causing a 5% drop in downward irradiance at 500 nm and a short peak at 1600 nm. The empirical 7% error bar is also

shown. For the ER-2 altitude (blue and red lines), the model-measurement agreement lies within the measurement uncertainties, except for the 1600 nm upwelling irradiance where the model results are larger than the measurements. This could indicate that the effective radius in the model cloud was too low or that the measured upward irradiance was influenced by contributions from outside the model domain. The model-measurement agreement is worse at DC-8 altitude (green and magenta lines), especially in areas where the cloud optical thickness is low (before 15.38 h UTC and after 15.49 h UTC). There are several reasons for this. First, within clouds, the downward and upward irradiance are a strong function of altitude and even small mismatches between the vertical profile of cloud extinction (and effective radius) in the model and reality (that is, the actual altitude of the DC-8) will result in large differences. Second, as noted above, the vertical profile of cloud extinction (as derived from CRS) is only valid on the nadir track (i.e., the profile between ER-2 and DC-8) and does not represent the vertical cloud structure across the entire MAS swath. In some cases, cloud edge effects occur only in the model results or in the measurements because cloud gaps and cloud boundaries are not necessarily represented realistically in the simplistic cloud algorithm.

[23] The net irradiance is less sensitive to altitude; for wavelengths outside gas and cloud absorption bands, it is expected to be constant with altitude. The vertical difference of net irradiances on top and at the bottom of the cloud layer, that is, vertical flux divergence ( $\Delta F_V$ ), is shown in Figure 4 (500 nm and 1600 nm). At 500 nm wavelength, the clouds themselves do not absorb and atmospheric gas absorption is near zero (except for the ozone Chappuy band, but no significant ozone concentrations are present between the altitudes of the two aircraft). No absorbing aerosol particles were present. Therefore, negligible values are expected for  $F_{\text{abs}}$ . In absence of true absorption, positive values of  $\Delta F_V$  (apparent absorption) indicate that photons are lost through the sides of the cloud column ( $\Delta F_H < 0$ ); negative values (apparent emission) correspond to a net photon gain. The observations (black dots) are shown with error bars that were estimated from the individual absolute uncertainties as explained above. Throughout almost the entire leg, significant apparent absorption is observed that is not balanced by negative values. Averaged over the leg, a value of  $0.17 \text{ W m}^{-2} \text{ nm}^{-1}$  is



**Figure 4.** (a) Time series of measured (black dots) and modeled (blue dots) vertical difference of net irradiances at 500 nm, along with SSFR footprint-averaged optical thickness (red line). The dash-dotted green lines at UTC = 15.35 h and UTC = 15.44 h mark where spectra of  $\Delta F_V$  are shown in Figure 7. (b) As in Figure 4a, but for 1600 nm. In addition, results from the Independent Pixel Approximation (IPA) are shown (green symbols). The magenta symbols show the model results for  $\Delta F_V$  for the layer from 5 to 20 km, rather than the standard 9 (DC-8 altitude) to 20 km (ER-2 altitude).

found. In the modeled vertical flux divergence, by contrast, negative and positive  $\Delta F_V$  values are balanced throughout the model domain and  $\langle \Delta F_V \rangle = 0$  because  $F_{\text{abs}} = 0$  and  $\langle \Delta F_H \rangle = 0$ . The domain-averaged horizontal photon transport vanishes due to periodic boundary conditions. Open boundary conditions could not be used because they would have compromised energy conservation. The bias between observations and model varies between 0 and  $0.2 \text{ W m}^{-2} \text{ nm}^{-1}$  along the leg. In areas of moderate to high optical thickness (between 15.38 h and 15.49 h (1523–1529 UTC)), the modeled values lie within the uncertainty of the observations. At some places, the discrepancies are larger than the error bars, for example at UTC = 15.47 h. At this time, Figure 2 shows off-nadir track maxima of optical thickness. Probably, the vertical structure in these two columns was not properly captured by the on-track CRS profile.

[24] The red line shows the MAS optical thickness retrievals averaged within the SSFR footprint. The SSFR footprint is usually defined as a circle within which 50% of the ER-2-measured upward irradiance originates. Table 2 shows the size of the SSFR footprint diameter as a function of cloud-top altitude, or cloud top-aircraft vertical distance. In this case, the 50% footprint diameter is mostly contained within the model domain. However, the 66% or 90% footprints are considerably larger than the MAS swath. About 50% of the irradiance originates from areas that are not represented within the model domain.

[25] The limited model domain size (given by the MAS swath width) could be an explanation for the discrepancy between observations and model results. While photons are confined within the model boundaries in the calculations, they are not restricted in this way in the real world. If the measurement area is surrounded by regions of lower optical depth or even clear sky, a net transport of photons into these regions can occur (in the same way as between areas of different optical thickness within the domain). However, there are theoretical limits for the horizontal displacement of photons. For example, the mean horizontal distance traveled by transmitted photons is in the range of cloud geometrical depth

[Marshak *et al.*, 1995] (less for reflected photons). Although the GOES IR image shows that there are indeed areas without high clouds southwest of the flight track, they may be too far away to explain the observations.

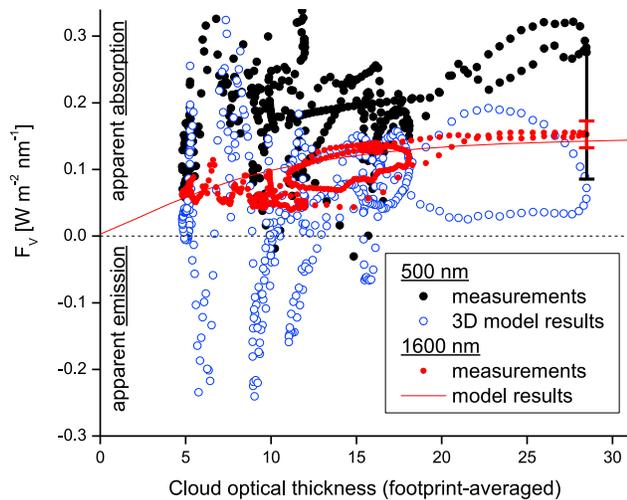
[26] For absorbing wavelengths, the root mean horizontal displacement of photons is much shorter than for non-absorbing wavelengths [Platnick *et al.*, 2001; Kassianov and Kogan, 2002]. It is therefore not surprising that the model-measurement discrepancy is much lower for 1600 nm (Figure 4b). In addition to the modeled  $\Delta F_V$  (blue circles), the green circles show the results from the independent pixel approximation (IPA) where horizontal photon transport is disabled in the model. Even in areas where Figure 4a indicates strong horizontal photon transport at 500 nm, the 1600 IPA model results are close to the full 3-D calculations. Thus, IPA provides a good estimate for true absorption in this case. The vertical position of the DC-8 within the cloud layer is of great importance for the measurement-model agreement at 1600 nm. The full-column absorption of the ice cloud ( $\Delta F_V$  from 5 km to 20 km, magenta symbols) does not agree with the measurements (column between 9 and 20 km).

[27] In addition to localized radiative smoothing, irradiance fields incur hemispherical (cosine-weighted) averaging of the underlying radiance fields, which could also contribute to the discrepancy since only about 50% of the irradiance origi-

**Table 2.** Footprint Diameter in km for an Aircraft Altitude of 20 km for Several Cloud-Top Heights and Corresponding Aircraft-Cloud Top Distances<sup>a</sup>

Cloud top (km)	8.0	10.0	13.0		
Aircraft-cloud top (km)	12.0	10.0	7.0	2.0	1.0
Irradiance ratio					
33% (cone angle 35°)	16.8	14.0	9.8	2.8	1.4
50% (cone angle 45°)	24.0	20.0	14.0	4.0	2.0
66% (cone angle 54°)	33.4	27.9	19.5	5.6	2.8
90% (cone angle 72°)	72.0	60.0	42.0	12.0	6.0

<sup>a</sup>The percentage under irradiance ratio indicates the fraction of upward irradiance originating from within the footprint diameter; the angle in brackets shows the corresponding cone opening angle of the SSFR.



**Figure 5.** Measured (black dots) and modeled (blue dots) vertical difference of net irradiances at 500 nm as a function of SSFR footprint-averaged optical thickness. For comparison, the measurements at 1600 nm are shown (red dots) along with the modeled true absorption (red line).

nates from within the MAS swath. The model results can be biased if the clouds outside the domain are not properly represented by the model cloud. These effects can only be examined by embedding the MAS-based cloud within the larger context of GOES-derived cloud fields. This is beyond the scope of this study. Until radiative transfer calculations are performed in an extended model domain, other causes for the discrepancies cannot be ruled out.

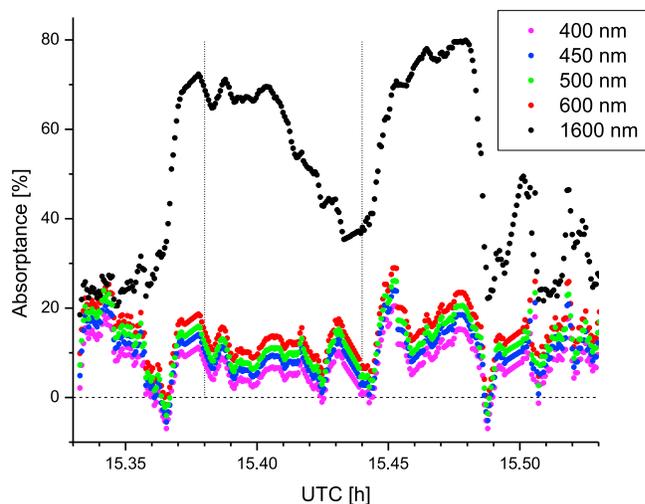
[28] Figure 5 illustrates the relationship between cloud optical thickness and  $\Delta F_V$ . The observations are shown for 500 nm (black dots) and 1600 nm (red dots), as a function of MAS-retrieved optical thickness (averaged over the SSFR footprint). The propagated error from the measurement uncertainties is shown at maximum optical thickness. The error is larger for 500 nm (only the negative error bar is shown) than for 1600 nm because 500 nm is near the maximum of the solar spectrum, and  $\Delta F_V$  is derived from the difference of large (500 nm) as opposed to small (1600 nm) quantities. In this particular case, the values of  $\Delta F_V$  are comparable in magnitude for the two wavelengths although the processes involved are fundamentally different: At 1600 nm, true absorption by ice crystals prevails. The modeled dependence of  $F_{\text{abs}}$  on optical thickness is shown as a red line. Observed (small) excursions from the modeled values can be explained by horizontal photon transport:  $\Delta F_V = F_{\text{abs}} - \Delta F_H$ . At 500 nm, by contrast, the true absorption is expected to be close to zero ( $F_{\text{abs}} \approx 0$ ), and  $\Delta F_V \approx -\Delta F_H$ . As discussed before, almost all the observations exhibit positive  $\Delta F_V$ , whereas the values from the 3-D model calculations (blue dots) do not show such a bias.

[29] There is some indication from both the model and observations that net transport of radiation occurs from optically thicker to thinner regions. Obviously a 1:1 relationship cannot be established, partly because net photon transport takes place between *local* maxima and minima of optical thickness. Net transport of radiation is not induced by optical thickness contrasts if they are separated by scales larger than the mean horizontal photon displacement. For

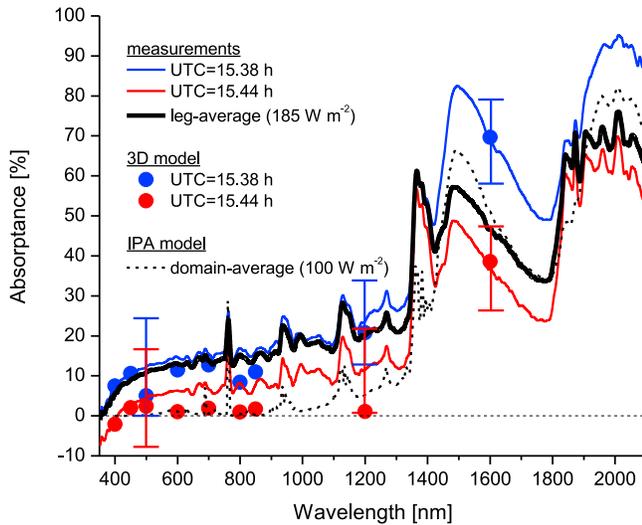
example, radiative smoothing, and thus  $\Delta F_H$ , at 1600 nm is suppressed in comparison to 500 nm because the absorption has a shortening effect on photon horizontal transport distances.

[30] For small optical thickness (5–13 in Figure 5), positive and negative apparent absorption occurs in the model calculations, uncorrelated with the optical thickness itself. These excursions from zero absorption suggest that in areas with sparse or thin cloud cover, factors other than large-scale horizontal cloud distribution dominate photon transport, such as vertical heterogeneities (multiple layers) and interactions with the surface.

[31] Figure 6 shows the time series of the measurement-derived apparent absorptance (defined as  $\Delta F_V/F_{\text{top}}^{\lambda} \times 100\%$ ) at four non-absorbing, and one absorbing wavelength. Along most of the leg, the apparent absorptance increases as a function of wavelength. This is further analyzed in Figure 7 where we show the spectral shape of measurement-derived and simulated apparent cloud absorptance in two different areas of the cloud: at UTC = 15.38 h (local maximum of  $\tau$ -red line) and at UTC = 15.44 h (local minimum of  $\tau$ -blue line), both of which are marked in Figures 4 and 6. Results from the 3-D model runs are shown as red and blue symbols. The black line shows the absorptance spectrum obtained when averaging observations over the entire leg from 15.33 h to 15.53 h. In the visible and very near infrared wavelength area, the leg-averaged spectrum is close to the high optical thickness case (blue spectrum); at near-infrared wavelengths, it is closer to the low optical depth case (red spectrum). The measured broadband apparent absorptance is  $185 \text{ W m}^{-2}$  (leg averaged),  $221 \text{ W m}^{-2}$  (optically thick case), and  $115 \text{ W m}^{-2}$  (optically thin case). The black dashed line shows the absorptance spectrum from a 1-D calculation where the optical thickness and effective radius input were obtained from averaging the properties throughout the model domain. It shows that true cloud absorption becomes non-zero only between 1000 nm and 1200 nm where the single scattering albedo drops below unity [Kindel *et al.*, 2010, Figure 1]. The 1-D modeled broadband-integrated value is  $100 \text{ W m}^{-2}$ , of which only  $9 \text{ W m}^{-2}$  occurs below 1000 nm.



**Figure 6.** Measured apparent layer absorptance at wavelengths from 400 to 1600 nm.



**Figure 7.** Spectral absorptance (or fractional absorption) at two selected points along the flight track (UTC = 1544, optically thin region; and UTC = 1538, optically thick region). The lines show the measurements with ice absorption bands around, for example, 1500 nm. The symbols show 3-D model results. The dashed line shows the 1-D calculated absorptance spectrum for domain-averaged optical thickness and effective radius.

The measured leg-averaged apparent absorption is composed of  $88 \text{ W m}^{-2}$  below and  $97 \text{ W m}^{-2}$  above 1000 nm. Above 1000 nm, the measured value ( $97 \text{ W m}^{-2}$ ) is only slightly higher than modeled ( $91 \text{ W m}^{-2}$ ). In ice absorption bands (e.g., 1500 nm), the spectral measurements (solid black line) are slightly lower than modeled (dashed line). Below 1000 nm, the disagreement between measured apparent absorption ( $88 \text{ W m}^{-2}$ ) and 1-D modeled (true) absorption ( $9 \text{ W m}^{-2}$ ) is much greater. The  $9 \text{ W m}^{-2}$  true absorption is caused by gas absorption, for example from the oxygen A-band around 762 nm, or water vapor absorption at 940 nm, 1140 nm, and 1350 nm (clearly visible in Figure 7). The water vapor absorption is rather weak because water vapor concentration is low at high altitudes. Subtracting the  $9 \text{ W m}^{-2}$  of gas absorption from the measured value of  $88 \text{ W m}^{-2}$  leaves  $79 \text{ W m}^{-2}$  that are unaccounted for by the 1-D model.

[32] The reasons for the discrepancies seen in the broadband domain/leg-averaged values can be understood by looking at the spectral effects along the leg: The measured and 3-D-modeled absorptance spectra on a point-by-point basis (optically thin and thick case) show considerable apparent absorption (5%–15%) across the entire visible wavelength range, with an upward slope at wavelengths short of 450 nm. For the higher optical thickness case (UTC = 15.38 h), the spectral behavior is reproduced by the 3-D calculations (blue circles), although not equally across the spectrum (e.g., 800 and 850 nm). This gives us some confidence that the observed effects are not measurement artifacts. Above 500 nm, the range of uncertainty of the absorptance measurement excludes zero, and the apparent absorption effect is statistically significant. For the low optical thickness case (1544 UTC), the 3-D model predicts near-zero apparent absorption across most of the visible range while the mea-

sured spectrum shows value of up to 10%. At 1200 nm, the measurement error bar only marginally contains the modeled near-zero apparent absorption. Overall, there is some indication that even the 3-D model underestimates the measured apparent absorption (especially in optically thin areas).

[33] The reason for the spectral slope at the shortest wavelengths is not entirely understood. It is likely due to the wavelength dependence of horizontal photon transport. *Marshak et al.* [2008] described a related effect for radiance, the so-called bluing of the atmosphere around clouds. Since molecular scattering is stronger at short wavelengths, enhanced reflected radiation near cloud edges gets scattered more effectively at short (“blue”) wavelengths and is redirected into satellite sensors. *Redemann et al.* [2009] describe a “reddening” of the atmosphere, caused by a combination of molecular scattering and aerosol scattering in the vicinity of clouds. Preliminary tests showed that switching off molecular scattering in the RT model did not change the slope significantly, thus ruling out molecular scattering as a cause for the spectral slope of the apparent absorptance.

[34] The spectral signature of the apparent absorption may prove important for cloud and aerosol remote sensing. If the reflectance at different wavelengths responds differently to cloud heterogeneity effects, there will be consequences for cloud retrievals. This spectral aspect of cloud retrieval biases occurs in addition to various 3-D effects that have been discussed in the literature. Owing to the different spatial scales, this additional effect may be more important for cirrus than for boundary layer clouds. A further implication is that any retrieval based on reflectance ratios in the near-UV and visible wavelength range, such as the aerosol index, will be distorted in the presence of cirrus, or other clouds. In the correction technique of *Ackerman and Cox* [1981], the visible wavelength for correcting net horizontal photon transport in absorption measurements needs to be chosen carefully, since the strength of horizontal photon transport varies throughout the non-absorbing part of the spectrum.

#### 4. Conclusions

[35] In this paper, we studied measured and modeled solar spectral absorption, based on data from the NASA TC<sup>4</sup> experiment in Costa Rica (2007). Most previous studies sought to infer true absorption  $F_{\text{abs}}$  from measurements of vertical flux divergence. This is problematic in heterogeneous clouds where horizontal fluxes occur. We therefore focused on apparent cloud absorption (vertical flux divergence  $\Delta F_V$ ), a quantity that comprises net horizontal photon transport (horizontal flux divergence  $\Delta F_H$ ) as well as true cloud absorption,  $F_{\text{abs}}$ :  $\Delta F_V = F_{\text{abs}} - \Delta F_H$ . We used SSFR measurements of upward and downward spectral solar irradiance on board the NASA ER-2 and DC-8 aircraft that were flown in stacked formation above and below the outflow of a tropical convective system on 17 July 2007. NASA’s aircraft-ground communication tool (RTMM) allowed a close coordination of the two aircraft in time and space. In this way, the cloud field was sampled over 198 km, and a time series of apparent absorption was derived from the differences of above and below-cloud net irradiances. In addition, simultaneous cloud remote sensing data (MAS-derived horizontal distribution of cloud optical thickness, crystal effective radius, and cloud-top height, as well as CRS-derived cloud

extinction profiles) were available from the high-flying aircraft. This allowed generating a 3-D model cloud that could be used as input to 3-D radiative transfer calculations to validate the measurements on a point-by-point basis along the entire flight leg. The spectrally resolved point-by-point approach allows the understanding of the effects of horizontal photon transport in greater detail than previously possible: For the first time, we were able to determine the spectral shape of the vertical net flux difference (apparent absorption), and to reproduce it with model calculations. We found considerable positive apparent absorption in the visible wavelength range where clouds do not absorb ( $F_{\text{abs}} = 0$ ) that could, at least in part, be explained by net horizontal photon transport. Below 500 nm, the apparent absorption decreases with wavelength and can become negative, thus entailing apparent emission of blue to near-UV radiation by clouds. The effective radius in the model may have been slightly underestimated, but major adjustments of the effective radius like in the work of *O'Hirok and Gautier* [2003] were not required to achieve model-measurement agreement in the true absorption. For non-absorbing wavelengths, measured apparent absorption exceeded 3-D model calculations at various points along the leg and averaged over the entire leg. The GOES-IR image indicates that the sampled cloud field was surrounded by areas of lower optical thickness or cirrus-free sky which could give rise to a net loss of photons from the sample area (unaccounted for by the model), thus explaining the enhanced value of apparent absorption in the observations. It was, however, beyond the scope of this study to explore whether including the areas around the sample cloud in the model calculations would support this hypothesis and thus fully resolve the reasons for previously observed “absorption bias.”

[36] The bias between measured leg-averaged apparent absorption below 1000 nm ( $88 \text{ W m}^{-2}$ ) and the 1-D-modeled value ( $9 \text{ W m}^{-2}$ ) is only partially resolved by looking at the spectral and spatial (temporal) details: While 3-D calculations of apparent absorptance are in agreement with the measurements in optically thick regions, there is some indication that even the 3-D model underestimates the apparent absorption in optically thin regions, which could be explained by the hypothesized net photon loss into the surrounding regions (not included in the 3-D model domain) that have even lower optical depth.

[37] Over what scales photons can effectively be transported within clouds, or away from cloud systems into clear-sky areas is an open question. For boundary layer clouds, theoretical limits exist for the root mean horizontal photon displacement [*Platnick*, 2001]. On average, the geometrical distance does not exceed the vertical extent of a cloud layer [*Marshak et al.*, 1995]. When sampling clouds over areas that are larger than this distance, the net horizontal photon flux is expected to be balanced ( $\langle \Delta F_H \rangle = 0$ ). Those distances might be larger in high-cloud systems, especially when multiple layers are involved. Moreover, the geometrical averaging inherent to irradiance introduces different effects for boundary layer clouds and large-scale convection systems, simply because of the different dimensions. *Kindel et al.* [2010, Figure 11] shows that irradiance-based retrievals of cloud optical properties of anvils are biased low with respect to radiance-based counterparts, because of the influence of clear-sky areas beyond the imager's swath.

[38] A different manifestation of net horizontal photon transport was observed by *Kalesse et al.* (submitted manuscript, 2010), using the same model cloud as employed in this study. The net outflow of photons from optically thick areas makes them appear darker and leads to an underestimation of cloud optical thickness by the imager. The opposite effect in optically thin areas does not fully compensate this bias and leads to a net effect of underestimation of optical thickness. As shown above, this effect is not spectrally neutral. Remote sensing techniques that rely on reflectance ratios at different wavelengths, such as the aerosol index, will thus be heavily affected in the presence of clouds.

[39] The physical basis of the spectral shape of near-UV and visible apparent absorption remains to be explored, as well as the scales over which horizontal photon transport occurs in high-cloud systems (for example, by embedding the MAS cloud scene in the larger context of GOES retrievals). In the future, new measurement techniques such as a payload that can be lowered down into and below a cloud from an aircraft [*Frey et al.*, 2009] will make apparent absorption measurements easier and will provide a link with cloud microphysics.

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