JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D9, 4273, doi:10.1029/2002JD002674, 2003

Quantifying the magnitude of anomalous solar absorption

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Received 19 June 2002; revised 23 September 2002; accepted 14 January 2003; published 9 May 2003.

[1] The data set from ARESE II, sponsored by the Atmospheric Radiation Measurement Program, provides a unique opportunity to understand solar absorption in the atmosphere because of the combination of three sets of broadband solar radiometers mounted on the Twin Otter aircraft and the ground based instruments at the Atmospheric Radiation Measurement (ARM) Southern Great Plains facility. In this study, we analyze the measurements taken on two clear-sky days and three cloudy days and model the solar radiative transfer in each case with two different models. On the two clear days, the calculated and measured column absorptions agree to better than 10 W m^{-2}, which is about 10% of the total column absorption. Because both the model fluxes and the individual radiometer measurements are accurate to no better than 10 W m^{-2}, we conclude that the models and measurements are essentially in agreement. For the three cloudy days, the model calculations agree very well with each other and on 2 of the 3 days agree with the measurements to 20 W m^{-2} or less out of a total column absorption of more than 200 W m^{-2}, which is again an agreement at better than 10%. On the third day, the model and measurements agree to either 8 or 14% depending on which value of surface albedo is used. Differences exceeding 10% represent a significant absorption difference between model and observations. In addition to the uncertainty in absorption due to surface albedo, we show that including aerosol with an optical depth similar to that found on clear days can reduce the difference between model and measurement by 5% or more. Thus we conclude that the ARESE II results are incompatible with previous studies reporting extreme anomalous absorption and can be modeled with our current understanding of radiative transfer. *INDEX TERMS:* 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; *KEYWORDS:* solar radiation, atmosphere absorption, clouds

Citation: Ackerman, T. P., D. M. Flynn, and R. T. Marchand, Quantifying the magnitude of anomalous solar absorption, *J. Geophys. Res.*, *108*(D9), 4273, doi:10.1029/2002JD002674, 2003.

1. Introduction

[2] Satellite measurements indicate that about 70% of the solar radiation incident at the top of atmosphere is absorbed by the Earth system. Models suggest that on a global average about a third of this absorption takes place in the atmosphere, primarily by water vapor, ozone, and condensed water and ice [*Kiehl and Trenberth*, 1997]. Calculations comparing a noncloudy column with a cloudy column, where the cloud in question is homogeneous and plane-parallel, show that high clouds generally reduce the column absorption while low clouds enhance the column absorption. On a global average, these two competing effects tend to average out, producing little difference in the average column absorption in cloudy regions versus noncloudy regions.

[3] Over the years, measurements of solar absorption in cloudy columns have indicated that greater absorption occurs in a cloud-filled column than can be accounted for by model calculations. This excess or anomalous absorption, defined as the difference between measured and calculated absorption (not as the difference between cloudy and clear columns), was generally found to be on the order of a few to 10% and various mechanisms were proposed to account for it [*Stephens and Tsay*, 1990]. Most of the scientists interested in the problem viewed it as intriguing but thought that it could be explained by proper accounting of cloud inhomogeniety and microphysical structure. This view changed abruptly in 1995 with the publication of two articles that claimed excess absorption on the order of 40% or more [*Cess et al.*, 1995; *Ramanathan et al.*, 1995] and a third that claimed significant excess absorption in tropical cirrus clouds [*Pilewskie and Valero*, 1995]. These three articles provoked a sizable number of further studies, some climatological in scope [see discussion by *Collins*, 2001], some theoretical [e.g., *Ackerman and Toon*, 1996; *Kiehl et al.*, 1995] and some focused on specific case studies [e.g., *Li et al.*, 1999].

[4] Between 22 September and 1 November 1995, the Atmospheric Radiation Measurement (ARM) Program

[*Stokes and Schwartz*, 1994], sponsored by the Department of Energy, conducted the ARM Enhanced Shortwave Experiment (ARESE) at its Southern Great Plains (SGP) Facility in north central Oklahoma. The ARESE experiment was based on simultaneous, matched flights of a high-level Egrett and a low-level Twin Otter aircraft. ARESE was plagued by the absence of clouds and obtained observations on only a few cloudy days, of which only 1 day was completely overcast. The initial analyses of the ARESE data [*Zender et al.*, 1997; *Valero et al.*, 1997] concluded that this overcast day showed excess absorption on the order of 100 W m^{-2}. Considering that model calculations of the situation on this day give values on the order of 185 W m^{-2}, these results represented a very large deviation from existing theory, which led to the suggestion that some completely unknown absorber or physical process must be at work in the atmosphere. However, subsequent aircraft experiments by the British [*Francis et al.*, 1997] and the Japanese [*Asano et al.*, 2000] showed no deviation of measured from calculated absorption that exceeded more than about 10%. The situation was further complicated by the fact that later analyses of the ARESE data indicated that the fluxes measured by the downward-looking total solar broadband radiometer on the Egrett on the single overcast day (30 October) were not consistent with GOES satellite data [*Valero et al.*, 2000] or data from a short-wave spectrometer that was also downward looking from the Egrett aircraft [*Li et al.*, 1999; *O'Hirok et al.*, 2000]. The inconsistency between the GOES and broadband radiometer measurements have led the broadband radiometer principal investigator to suggest that the instrument data may have been contaminated by oil leaks from the landing gear or localized icing, which caused an underestimate of the upward flux and an overestimate of the absorption [*Valero et al.*, 2000]. Given this confused situation, ARM decided to host a second experiment, dubbed ARESE II, at its SGP site. In this paper, we discuss the results of the broadband observations and our efforts to model the situations observed during ARESE II. We give a brief description of the experimental data and the two different models that we used, followed by a comparison of the measured and computed absorption.

2. The ARESE II Data

[5] The ARESE II experiment plan was designed to take advantage of the extensive instrumentation deployed at the ARM SGP central facility, where continuous observations of the surface radiation budget and cloud properties are available. (Detailed information on the ARM program and its data archive is available at www.arm.gov.) In order to reduce uncertainties caused by 3D cloud structure and ice and rain, the experimental plan focused exclusively on extended stratus decks existing in environmental conditions, which indicate that the clouds should be composed only of liquid water. Fluxes above cloud were measured using a Twin Otter aircraft, which has a typical maximum flight altitude of about 7 km above ground level at the SGP site. Further details about ARESE II are available at http://armuav.atmos.colostate.edu/uavw00/uavw00.html.

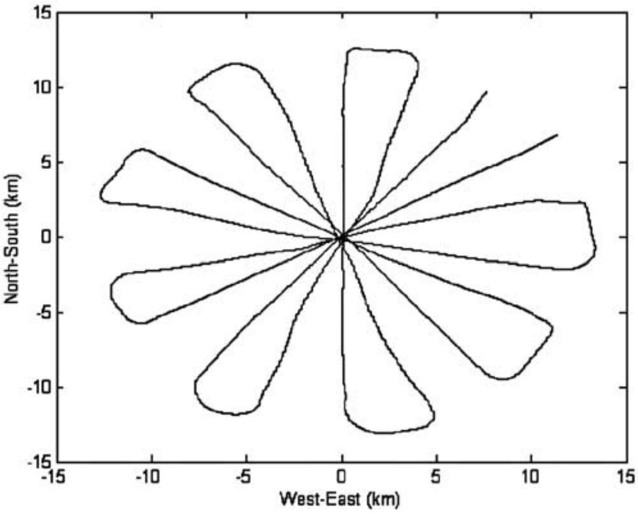

Figure 1. Daisy pattern flown by the Twin Otter aircraft at an altitude of approximately 7 km on 27 February. The (0, 0) point of the diagram corresponds to the location of the central facility of the ARM Southern Great Plains site. Similar patterns were flown on other days.

[6] In this study, we use data from the surface solar radiometers, the cloud radar, the microwave radiometer, the Raman lidar, the micropulse lidar, and sonde releases. The surface radiometer data that we use are from the Solar Infrared Radiation Station (SIRS), which is the standard ARM system at the SGP. For the downward solar flux, we use the sum of a direct irradiance and a shaded diffuse measurement. The latter is made using an Eppley black and white radiometer, which requires no thermal offset correction [*Dutton et al.*, 2001; *Long et al.*, 2001]. The upward solar flux is measured using a downward facing radiometer mounted on a 10-m tower. The Twin Otter aircraft flew a daisy pattern (Figure 1) over the central facility at maximum altitude (about 7 km) and then typically flew a few legs at low altitude (limited to about 0.4 km) on each day of the experiment. The Twin Otter carried three different aircraft sets of upward and downward-looking solar radiometers: (1) the Total Shortwave Broadband Radiometer [TSBR; *Valero et al.*, 2003], (2) the CM21 instruments of the Meteorological Institute (MRI) of Japan [*Asano et al.*, 2000], and (3) the CM22 instruments of Sandia National Laboratory. The CM21 and CM22 are commercial instruments manufactured by Kipp and Zonen. All radiometers were calibrated against the same standard instruments [*Michalsky et al.*, 2002] and each investigator group was responsible for providing calibrated and properly navigated data to the archive. In our research, we use these data sets with no further corrections or adjustments.

[7] The ARESE II experimental team chose the daisy pattern to provide a series of passes over the central facility at different relative solar azimuths in order to minimize any directional bias that might be present in the mounting of the upward-looking radiometers. As we show later, the radiometer investigators did an excellent job of removing any such bias from the data. The length of the individual legs was intended to give about 10 min of level flight in order to allow the radiometers to equilibrate and provide a meaningful data sample. We

had to decide as to how to analyze these data. After some experimentation, we decided to treat each leg (one pass over the central facility) as an independent event. Thus we select all the data points on a given leg that have less than approximately 2° of pitch and 2° of roll from level and average them to get a mean value for that leg. We average the SIRS data at the central facility for the same time period to obtain the solar flux at the surface. We also use the same averaging period for data inputs for our model calculations. The advantage to this approach is that we use as much of the data as possible. The disadvantage is that the aircraft measurements at the ends of the legs may be some considerable distance from the central facility, which introduces variability due to the spatial inhomogeneity of the clouds and underlying surface. We note that the absorption values resulting from our approach do not differ appreciably from those obtained by the conditional sampling approach devised by *Oreopoulos et al.* [2003] and the more restrictive use of aircraft data by *O'Hirok and Gautier* [2003]. The former approach samples the broadband absorption record using only those times when the absorption at 500 nm (measured by a different radiometer) is near zero, while O'Hirok uses only those measurements when the aircraft is within a few kilometers of the central facility. Because the cloud decks were extensive and homogeneous to some degree, all three methods produce similar results for the cases examined here.

[8] The various aircraft instrument groups all operated ground-based instruments at the SGP central facility that were similar to the aircraft instruments. As a result of the calibration efforts [*Michalsky et al.*, 2002], the measured fluxes from these instruments generally agreed with the SIRS measurements to about 10 W m^{-2}, but there were day-to-day differences. We proposed to use the SIRS measurements only at the surface to remove these additional differences and simplify the interpretation of results. This choice has very limited effect on any of our conclusions.

[9] Obtaining closure of the absorption problem requires a measure of the reflected solar flux at the surface. In field programs such as this over land, there is no ideal way of obtaining this quantity. During ARESE I, two aircrafts were used flying in a stacked mode and the upwelling flux measured on the lower aircraft provided the reflectance. However, the cosine-weighted area viewed by that radiometer was much smaller than that viewed by the higher aircraft, leading to an uncertain error in the measured column absorption. Only one aircraft was used during ARESE II, so the only way to determine the reflected solar radiation was to apply a surface albedo value to the downwelling radiation measured at the surface. The SGP central facility has instruments mounted at several different heights over different surfaces. We chose to use the flux measured on a 10-m tower located over grass. The grass during the ARESE II period was just beginning its spring growth so the surface reflectivity measured over grass decreased steadily during this period. The larger SGP site, however, contains a mixture of pasture (grass) and winter wheat, as well as some limited area of trees. The central facility site also includes a reflected solar flux measurement on a 25-m tower over a wheat field. The albedo for the wheat field actually increases slightly during the ARESE II period despite the fact that the wheat grows more quickly than the grass. This happens because the wheat field is dark dirt, which has a low albedo, before the wheat grows, while the grass area is covered by grass stubble from the previous year's growth, which has a somewhat higher albedo.

[10] Flux measurements taken during the low-altitude aircraft legs permit an estimation of surface albedo, which can then be applied to the SIRS downwelling measurement to give a second measure of upwelling flux. The aircraft albedo runs were made at heights of 400–700 m above the surface so the reflected flux integrates over some mixture of land surface types, which produces an albedo value that is different from the value at the central facility. We include both measures of upwelling flux in our analysis for the sake of comparison and completeness. The surface albedo was characterized spectrally by measurements of several different land cover types surrounding the SGP site taken on 3 March using a spectrometer. The spectral albedo profile based on these measurements is scaled on any given day to broadband albedo values calculated from either the 10-m tower or the low-level aircraft measurements.

[11] The radiative transfer models that we use require inputs of temperature and humidity profiles, cloud column liquid water, cloud microphysics, and cloud base and top, as well as spectral surface albedo. In order to match the observed surface solar fluxes for clear-sky cases, the models also require aerosol properties as inputs. The temperature and humidity profiles were obtained from radiosonde launches at the central facility. The humidity profiles from these launches are scaled to the water vapor path values retrieved from the microwave radiometer. Profiles between launch times are produced using the measured water vapor path and interpolated vertical profiles. We also used the microwave brightness temperatures to retrieve liquid water path. The standard ARM retrievals use a modified statistical retrieval method [*Westwater*, 1993]. We improved these retrievals using an actual physical model. This model calculates the two-channel microwave brightness temperatures using an initial profile of temperature and water vapor from the temporally nearest radiosonde launch and cloud boundaries based on the radar and lidar measurements. The total water vapor and liquid water values are then perturbed iteratively to produce convergence between measured and calculated brightness temperatures. This procedure is more involved and takes longer than the standard retrievals but produces a more accurate result. Although we had some in situ microphysical measurements, their quantity ranged from good to none for the three cloudy days. In order to close the cloud optical property calculations in a uniform manner on all 3 days, we opted to specify a size-distribution shape with a variable particle-effective radius. We then iterated the effective particle radius of the distribution until we matched the measured downward solar radiation at the surface. A separate calculation and iteration was carried out for each leg on each cloudy day. As a sensitivity test, we carried out the same procedure for one set of flight legs but iterated until we reached convergence with the reflectance measured by the Otter. The implications of this procedure on the calculated absorption are discussed below. Cloud base and top were determined from lidar and radar profiles [*Clothiaux et al.*, 2000].

[12] For model calculations on clear days, we use aerosol optical depths obtained from multifilter rotating shadowband radiometer (MFRSR) measurements [*Michalsky et al.*, 2001] and aerosol asymmetry factor and single-scattering albedo values calculated from the mineral and average continental aerosol types of *d'Almeida et al.* [1991]. These two aerosol types are representative of aerosol typically observed at the SGP during late February and March. Carrying out model calculations using both aerosol types gives an indication of the uncertainty of the absorption associated with the uncertainty of the actual aerosol composition.

[13] ARESE II extended over a 6-week span in order to provide a reasonable probability of obtaining several extended single-layer stratus decks not containing ice or substantial rain. Stratus decks approximating these conditions occurred on 3 days, 3, 21, and 29 March, all of which we analyzed. The deck on 3 March consisted of trailing stratus behind a frontal system and extended from approximately 700 to 1500 m. Cloud optical depths on this day were rather moderate, on the order of 30. The deck had no ice and very little, if any, drizzle drops. The deck also had some small breaks. These small breaks have a greater influence on the variability of the downwelling surface flux than on the reflected flux at the aircraft due to the low cloud base height. Our analysis of the surface data indicated that the effects were small when averaged over each flight leg. The Otter collected data in a daisy pattern at altitude (about 7 km) for about 2 hours and then made an undercloud albedo run at about 400–700 m before landing. The North Dakota Citation sampled cloud microphysical properties during the period of the Otter over flight. On this day, the microphysical data are fairly complete and include profiles extending from cloud base to cloud top. The cloud deck on 21 March was also trailing stratus behind a front, but was thicker (1000–3000 m) and had greater optical depths, on the order of 45–50. The cloud thinned over the course of the flight, with cloud base rising to above 2000 m by the end of the flight. The cloud deck on this day, as well as on 3 March, shows banded structures that can be seen in satellite imagery. On 21 March, some patches of thin cirrus drifted over during the flight but their effect on the solar flux appeared to be minimal, and as discussed later, we screened aircraft legs to remove those with cirrus present. The flight pattern was similar with 2 hours spent at altitude, followed by a short albedo run under cloud. Drizzle was observed during this flight, and once again, the North Dakota Citation acquired simultaneous microphysical data. However, the data on this day were more limited than on 3 March and the profiles did not extend through the entire depth of the cloud. A very large stratus deck developed on 29 March following a substantial outbreak of convection in the Oklahoma area that slowly drifted off to the north and east. Cloud base was very low, on the order of a few hundred meters and cloud top was a bit above 2000 m. Cloud optical depths were substantial, reaching values of 65 or more. Drizzle did occur on this day, but no ice was observed. The Otter flew a daisy flight at altitude for about 2 hours and then made a low-level albedo run before landing. No microphysical measurements were made on this day.

[14] In addition, we analyzed data from two clear days, 27 February and 20 March. On both these days, the Otter flew a series of low-level legs at about 400–700 m to measure the surface albedo and then flew a daisy pattern at 7 km to obtain the net flux at that altitude. There were no clouds in the area on either day and aerosol loadings were small, with optical depths of 0.1 or less.

3. The Models

[15] There are a wide variety of radiative transfer models of varying characteristics that are available to us, as well as others. We chose to use two different models, both of which are well documented in the literature, including comparisons to other model calculations, and which treat solar absorption and scattering in a detailed, explicit manner.

[16] Our model, called RAPRAD, is a δ2-stream discrete ordinate code [*Toon et al.*, 1989] with a correlated-k spectral integration [*Kato et al.*, 1999]. The solar spectrum is divided into 32 spectral intervals, and k-distributions have been developed for each spectral interval as a function of pressure and temperature. In spectral regions that have overlapping absorption by two gases, we assume that the overlap is random and the two k-distributions are multiplied together. The identical correlated-k integration was used with a Monte Carlo code in a radiation code comparison study [*Barker et al.*, 2003] and produced agreements of better than 1% in clear-sky absorption compared to a standard line-by-line code. For monochrome, near-conservative scattering cases, the δ2-stream approximation is typically accurate to a few percent. This accuracy actually improves with increasing absorption, because detailed representation of the scattered field is less important, and for integration across a broad spectral band, because the errors are to some extent random. Consequently, the inherent numerical accuracy of a RAPRAD calculation relative to a more detailed model is on the order of a percent or two. Note that this assessment does not address the uncertainty in the calculation due to uncertainties in the inputs. For the cloud calculations in RAPRAD, we used a single-mode lognormal size distribution with a width of 0.38 and a mean radius determined by the iteration process described above.

[17] The second model that we used is SBDART, obtained from the University of California at Santa Barbara [*Ricchiazzi et al.*, 1998]. This code also uses a δ2-stream discrete ordinate approximation, but has a very different spectral integration scheme. SBDART uses the LOWTRAN spectral grid, which is considerably of higher resolution than that used by RAPRAD. In each spectral interval, the transmission function calculated by LOWTRAN is fit with a three-term exponential sum and the resulting exponents are used in the discrete ordinate code (please note that the newly released version of SBDART now uses a correlated-k spectral grid. Our calculations were performed with the original version). The disadvantage of this approach is that the pressure dependence of the transmission function cannot be accounted for explicitly, but only in some approximate fashion using pressure scaling. As demonstrated later, the two codes produce similar results despite their quite different treatment of gaseous and aerosol absorption. For the cloud calculations

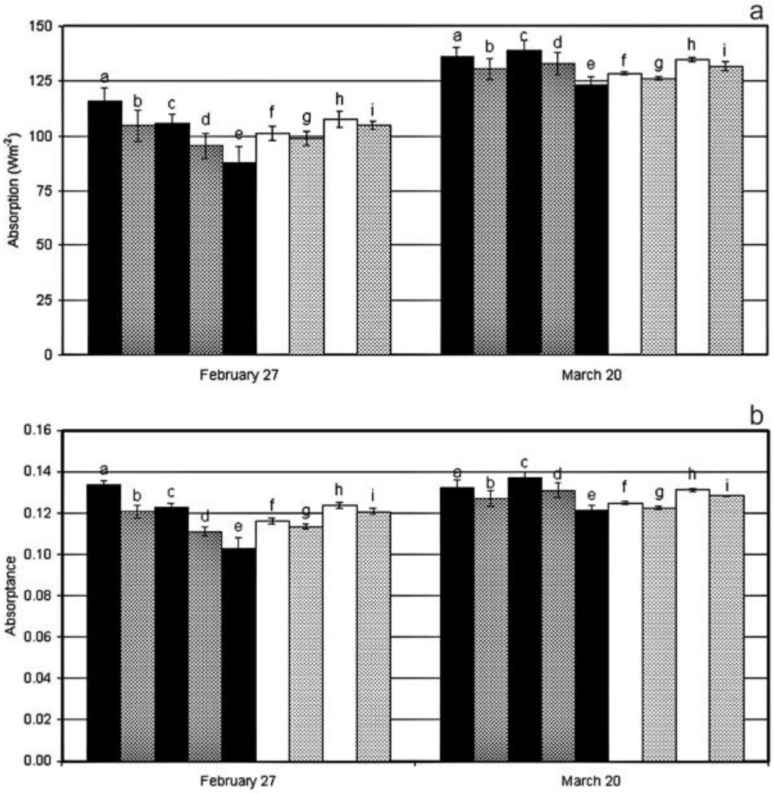

Figure 2. (a) Clear-sky absorption and (b) absorptance values for the atmospheric column from the surface to 7 km on 27 February and 20 March. The bars labeled a, c, and e are calculated using aircraft data from the TSBR, CM22, and CM21 instruments, respectively, at 7 km and the surface albedo measured by the 10-m tower at the SGP central facility. Bars b and d are calculated from the TSBR and CM22 instruments at 7 km and their respective albedo values calculated from low-level aircraft passes. Bars f and g are model calculations using RAPRAD with a mineral and an average continental aerosol, respectively. Bars h and i are model calculations using SBDART with a mineral and an average continental aerosol, respectively.

in SBDART, we used a modified gamma size distribution with a width parameter of 7 and the mean radius determined by iteration.

4. Results

4.1. Clear-Sky Cases

[18] We expect a comparison of clear-sky measured and modeled absorption to produce close agreement. While the agreement is indeed good (Figure 2), there are some interesting differences. The first five bars on each day in the figure represent the measurements. In all cases, we use the same downwelling surface flux, measured by the ARM SIRS system, but the net flux at the aircraft comes from the TSBR, CM22, and CM21 instruments, respectively. As noted earlier, we use two values of the albedo, one from the 10-m tower at the SGP site and the other from the average of the low-level Otter measurements determined separately using either the TSBR or CM22 upwelling and downwelling fluxes. The CM21 downward-looking radiometer on the Otter provided inconsistent results over the course of the ARESE II experiment, particularly with regard to the albedo measurements. Therefore we have chosen to omit the CM21 albedo comparisons. Looking first at the absorption calculated using the upwelling flux from the 10-m tower, we see that the CM21 values are consistently lower than the other two data sets by 15-20 W m^{-2}. (The actual absorption values are given in Table 1.) Because we are using the same surface fluxes in each case, these

Table 1. Clear-Sky Measured and Modeled Values of Absorptance (Abt) and Absorption (Abs)[a]

	Feb. 27				March 20			
	Abt	SD	Abs	SD	Abt	SD	Abs	SD
TSBR tower	0.134	0.002	116	6	0.132	0.004	136	5
TSBR aircraft	0.121	0.003	105	7	0.127	0.004	131	5
CM22 tower	0.123	0.002	106	5	0.137	0.003	139	4
CM22 aircraft	0.111	0.002	96	6	0.131	0.004	133	5
CM21 tower	0.103	0.005	88	7	0.121	0.003	123	4
RAPRAD mineral	0.116	0.001	101	3	0.125	0.001	129	1
RAPRAD cont.	0.114	0.001	99	3	0.123	0.001	126	1
SBDART mineral	0.124	0.002	108	4	0.131	0.001	135	1
SBDART cont.	0.121	0.001	105	4	0.128	0.001	132	1

[a] The values are flight averages, and the standard deviations represent the leg-to-leg variability. Measured values are given for two different surface albedo values and modeled values for two different aerosol types. Units are watts per square meter for the absorption and corresponding standard deviation.

Table 2. Surface Albedo Values, Averaged Over the Flight Time (Tower) or Over Low-Level Flight Legs for the Radiometer Pairs (TSBR and CM22)

	Feb. 27	March 3	March 20	March 21	March 29
Tower	0.202	0.178	0.184	0.181	0.158
TSBR	0.186	0.209	0.178	0.188	0.244
CM22	0.188	0.206	0.177	0.214	0.274

differences are only due to differences in the aircraft flux measurements. The CM22 and TSBR values differ by 5–10 W m^{-2}, with the TSBR being greater on one day and the CM22 on the other. If we use the aircraft albedo values, which are each lower than the 10-m-tower value (Table 2), the absorption decreases by 10 W m^{-2} on 27 February and 5 W m^{-2} on 20 March.

[19] The identical data are presented in Figure 2b in absorptance, rather than absorption units. Absorptance is simply the layer absorption divided by the incident solar flux at the aircraft altitude, which means that it is the fraction of the incident solar radiation at 7 km absorbed in the atmospheric layer between 7 km and the ground. Using absorptance has the advantage of removing, to first order, the effect of the varying solar zenith angle from leg to leg and day to day. Care must be taken in comparing absorptance values from ARESE II with values from other experiments, however, because the calculated absorptance does depend on the thickness of the atmospheric layer as well as the properties of that intervening layer. Except for the CM21 measurements on 27 February, the measured absorptance values vary by less than 2.5% of the incident solar flux on 27 February and 1.5% on 20 March.

[20] The small "error bars" on the larger bars in Figure 2 and subsequent figures do not represent actual errors. The height of the main bar gives the average value of absorption for all flight legs on a given day; the small bars indicate the standard deviation of the flight leg values, and thus, represent the consistency of the conditions and measurements over the 2-hour flights. On these 2 days, atmospheric conditions changed very little during the course of the flights as indicated by the very small standard deviation values evident in the model calculations. The roughly ±5 W m^{-2} standard deviation in the measured values is actually quite good, given all the potential sources of difference. Some portion of these leg-to-leg differences is certainly due to changes in the underlying surface albedo along the different flight legs, while some other portion is probably due to differences in correcting the downwelling solar flux at the aircraft for aircraft motion.

[21] For the clear-sky cases, separate calculations were carried out with both models for both aerosol types (Figure 2). The model-calculated absorptions differ from each other by about 5 W m^{-2} with SBDART being slightly greater than RAPRAD. For both models, the absorption calculations using a mineral aerosol are about 2–3 W m^{-2} higher than the calculations using an average continental aerosol. Comparison of the calculated surface downwelling flux with the SIRS measurements on 20 March (Figure 3c) shows that for the same aerosol model, RAPRAD is more transmissive than SBDART by about 10 W m^{-2}. In simulations done without any aerosol, we have traced this difference to the computed water vapor absorption. Comparisons between RAPRAD and line-by-line codes for some specific cases show agreement at the level of 1% in absorption [*Barker et al.*, 2003]. We suspect that the difference between SBDART and RAPRAD can be traced to the use of exponential sums rather than correlated-k theory distributions, but further research is needed to confirm this hypothesis. By coincidence, the 10 W m^{-2} difference in water absorption is almost exactly the difference produced in either model by using the average continental or mineral aerosol. Based on the work of *Dutton et al.* [2001] and *Long et al.* [2001] and the ARESE II calibrations reported by *Michalsky et al.* [2002], we think that the SIRS measurements are accurate to about 1% or 10 W m^{-2} for the sum of direct plus diffuse measurements for clear skies. Because we do not have information about the aerosol composition, these results show that by choosing an appropriate aerosol for either model we can match the observed flux to an arbitrary accuracy and that we cannot discriminate between radiative transfer and aerosol models by comparison with the SIRS.

[22] The values of downwelling solar radiation at the aircraft level on 20 March (Figure 3a) illustrate another complicating factor in the analysis. As expected, both models show smooth curves varying from minimum to maximum by about 35 W m^{-2} due to changes in the solar zenith angle around local solar noon. The agreement between the models is about 2 W m^{-2}, which can be attributed to slight differences in spectral grids and treatments of water vapor and ozone absorption. The measurements show the same general trend and range, but they are offset from each other by as much as 20 W m^{-2} and show leg-to-leg variations of 5–10 W m^{-2} that are not associated with solar zenith angle changes. These offsets and variations change somewhat from flight to flight but generally fall within the same range. The variations arise from the fact that the measurements are very sensitive to aircraft pitch and roll motions relative to the azimuth and zenith of the Sun. We want to emphasize that in our opinion the principal investigator teams have produced data sets of exceptionally high quality, but this level of uncertainty cannot be reduced without mounting the radiometers on an inertial platform. The offsets are an indication of the calibration uncertainty in hemispheric radiometers mounted on aircraft. These differences are only 2% of the incident signal, which is an excellent result, and are within our quoted measurement uncertainty of 3% for broadband pyranometers. As expected, the upwelling measurements made at the Otter altitude (Figure 3b) show much less variation in both the models and the measurements. However, measurement offsets remain. A comparison of these figures with the column absorption (Figure 3d) shows that the reason the TSBR and CM22 absorptions are approximately the same is that both the upward and downward fluxes are offset by the same amount, producing a very similar value of the net flux. The CM21, however, agrees with the CM22 for the downwelling and the TSBR for the upwelling, which produces a difference of about 15–20 W m^{-2} in absorption. The model absorption values are constant over the flight and are in good agreement with the measurements (Figure 3e).

[23] The choice of the surface albedo value and its effect on the absorption warrants some discussion. Using the aircraft albedo rather than the 10-m albedo changes the

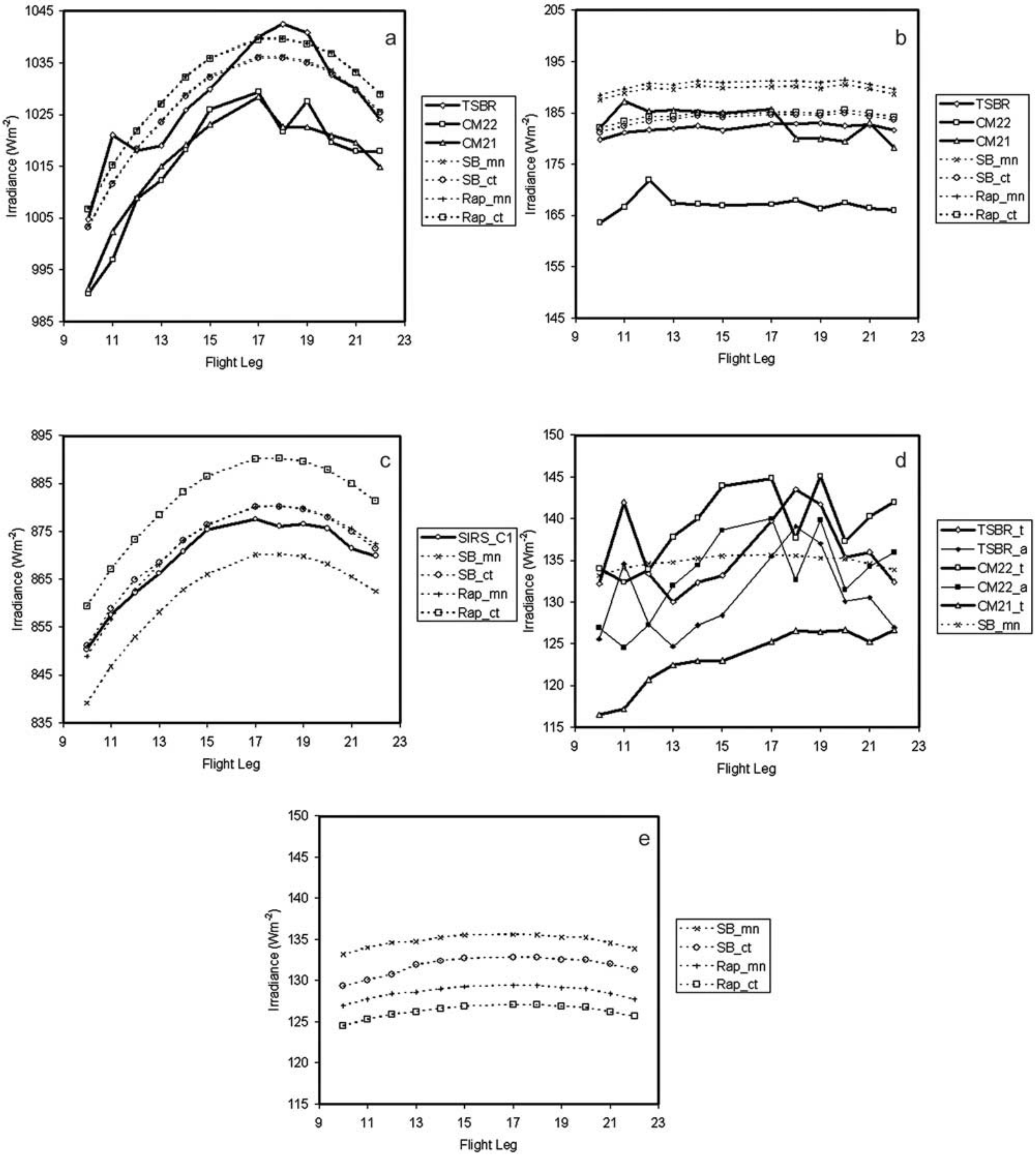

Figure 3. Comparison of measured and modeled quantities on 20 March, a clear day. (a) Downward flux at 7 km. Legend identifies the three radiometers and the two models, each using two different aerosol types. (b) Upward flux at 7 km. (c) Downward flux at the SGP central facility. (d) Measured layer absorption calculated using either the tower or aircraft albedo (one model curve is shown for comparison purposes). (e) Calculated layer absorption for two models, each using two different aerosol models.

measured column absorption uniformly by about 5 W m^{-2} (Figure 3d) because it enters the equation for the net surface flux as a direct multiplier of the surface downwelling flux. Changing the surface albedo in the models by the same amount (0.01) has essentially no impact on the calculated column absorption. This difference arises from the fact that the model calculates the absorption spectrally. Photons in strong gaseous absorption bands are absorbed regardless of the albedo of the underlying surface and photons in non-absorbing bands simply pass through the atmosphere upon

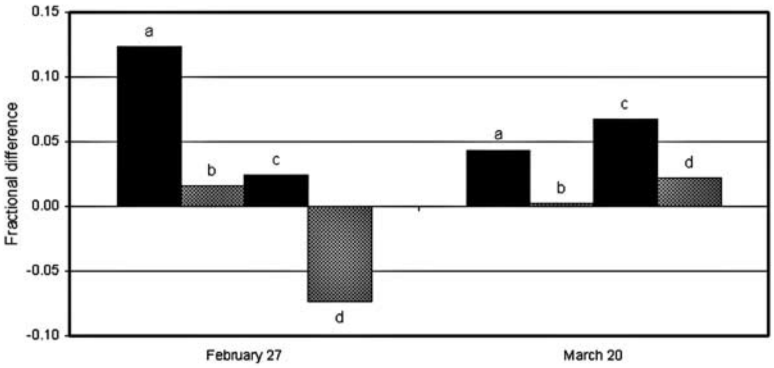

Figure 4. Fractional absorption difference defined as measured minus model divided by the model value. Bars a and c use the TSBR and CM22 aircraft fluxes with the tower albedo, while bars b and d use the low-level aircraft albedo values.

reflection. Changing the albedo only affects the absorption in weak bands and then only slightly. Consequently, the uncertainty in the measurement of surface albedo directly leads to a corresponding uncertainty in the measured absorption but essentially no significant uncertainty in the calculated absorption.

[24] We include calculations for both local and aircraft albedo values because both measurements have distinct problems. The 10-m tower measurement is stable and well understood, but represents only a local value and thus may not be representative of the larger site area. As seen in the first row of Table 2, the tower values decrease over the ARESE II period due to the growth of green grass during this period. The aircraft albedo values are made over a larger area but suffer from several measurement issues. Because the aircraft runs are made in the boundary layer, the aircraft experiences a lot of pitch and roll, which has a serious affect on the downwelling solar measurement on clear days. Only a few low-level legs were flown and quite a few data points were removed from these samples because of aircraft orientation, leaving us with a fairly small sample at the end. The albedo values determined from the TSBR and CM22 pairs are consistent with each other up to 20 March, but differ by about 0.03 on 21 and 29 March. It is interesting to note that the aircraft albedo values are lower than the 10-m tower on both clear days (27 February and 20 March) but higher than the 10-m tower on the three cloudy days. Because a lower surface albedo translates into a lower value of atmospheric column absorption, using the aircraft albedo values reduces the measured column absorption on the clear days but has the opposite effect on cloudy days.

[25] We now turn to a comparison of the models with the measurements. Because we see no clear reason to choose between the two models, we opted to average the model values for each day and then plot the measured absorption minus the model average divided by the model average (Figure 4). On 20 March, the differences range from 0 to 6%, while on 27 February, they range from −7 to 12%. In absolute terms, these differences are all less than 15 W m^{-2}. The question then is whether this difference is significant given the uncertainties or errors in both the model calculations and measurements.

[26] We expect the uncertainty in the model calculations to be dominated by the differences in spectral integration schemes and by uncertainty in the actual input values. As a sensitivity test for the latter, we increased the water vapor column concentration in the models by 5%. This is a large but plausible error in the microwave radiometer measurement. This increase in water vapor increased the calculated absorption by less than 1%. Some uncertainty is introduced by the choice of aerosol model. The aerosol optical depths on these days are small, however, decreasing the single-scatter albedo slightly only increases the absorption by a couple of watts per square meter, as we have already noted. In short, the individual model absorption values are uncertain at the level of 1 or 2% due to uncertainties in the input values and the model itself. The difference between the two models for identical inputs is less than 5%, suggesting that the model absorption values are uncertain at the level of 5% for the noncloudy sky.

[27] The actual error (as opposed to variability) in the radiometer measurements is quite difficult to assess. Although the radiometers were all calibrated against the same standard on the ground [*Michalsky et al.*, 2002], there are some issues that need to be considered. First of all, the operating environment of the radiometers on the aircraft is obviously much different that on the ground. Despite every effort by the instrument groups to account for these differences in ambient temperature and ventilation, they undoubtedly produce some unknown error. Second, the absorption is computed from the net flux, which is obtained by differencing the hemispheric flux measured by the upward- and downward-looking radiometers. If both radiometers are calibrated against the same instrument on the ground, then one might assume that, to first order, any bias error in the two instruments would simply cancel out in the subtraction. This is actually not the case. Instrument error for these radiometers arises from two causes, the first being absolute calibration and the second being the cosine response of the instrument. The upward-looking radiometer sees a radiation field that is dominated by a direct beam. Hence the error in this measurement is strongly influenced by any small uncertainty in the cosine response at that particular direct beam angle. The downward-looking radiometer sees a diffuse field, so its error is dominated by the calibration

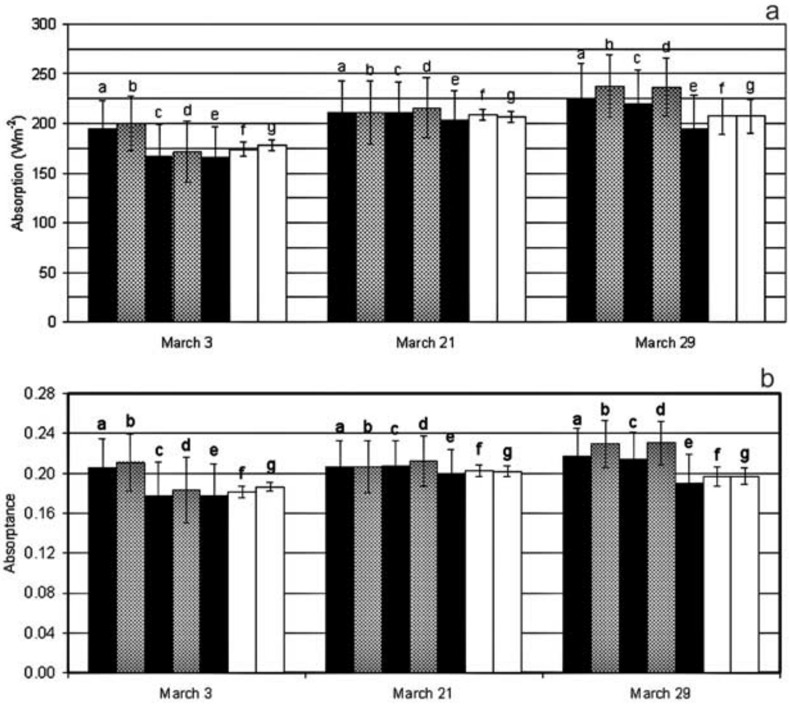

Figure 5. Same as Figure 2, but for the three cloudy days. Bars f and g are model calculations using RAPRAD and SBDART, respectively, but with no aerosol in the column.

uncertainty. Thus the errors in these two measurements do not necessarily cancel. We have no way of knowing what the actual error in the measured absorption is, but given the errors in each of the individual measurements and the spatial mismatch between aircraft and ground measurements, an error of at least 10 W m^{-2} certainly seems plausible. At this level of error, the agreement between the TSBR and CM22 measurements and the models is generally well within the uncertainties associated with them. The one outlier seems to be the TSBR measurement on 27 February using the 10-m albedo. Note, however, that the substitution of the Otter albedo drops this difference to less than 2%. At the same time, the similar change in albedo for the CM22 measurements changes the absorption from 2 to -7%. We conclude that, given the results discussed here, differences between measured and computed fluxes must exceed 10% at the very least in order to be considered significant.

4.2. Cloudy Absorption

[28] The cloudy-sky absorption from both measurements and calculations (Figure 5) is roughly a factor of 2 greater than the clear-sky absorption, which is consistent with our expectation that low clouds increase column absorption. The absorption increases from 3 March to 29 March, but the absorptance plot shows that this increase is due to a combination of increasing insolation and thicker clouds. The model absorptance values on 21 and 29 March are very similar, suggesting that the cloud absorption has largely saturated at optical depth values of 45. We can also see that there is some disparity among the results across the 3 days. On 21 March, all the measured and modeled values agree very well with each other. On 3 March, the TSBR absorption is clearly higher than the others, all of which are quite similar. On 29 March, the TSBR and CM22 measured absorption is clearly greater than the model values, especially when the Otter albedo values are used. The difference between the 10-m and Otter albedo values (Table 2) is greatest on 29 March, leading to a difference in measured absorption of between 15 and 20 W m^{-2}.

[29] The model calculations for the cloudy cases were carried out assuming locally plane-parallel clouds with constant microphysical properties and with no aerosols anywhere in the column. One of the limitations of the ARESE II measurement set is that we have no information about aerosol loading above, below, or within the cloud layer. Therefore we opted to insert no aerosol in our base calculations. The two models are in very close agreement with each other on all 3 days. As noted earlier, we constrained the effective droplet radius by fixing the liquid water path from the microwave radiometer (MWR) measurements and then varying the effective radius in order to match the solar broadband flux at the ground. We performed this iterative process using SBDART, which uses a gamma function for the cloud droplet size distribution, and then used the same effective radius in RAPRAD, which uses a lognormal function. The model runs, therefore use identical cloud properties and produce nearly identical absorption despite slightly different size distributions and gaseous absorption treatment.

[30] The small bars again indicate the standard deviation of the leg-to-leg values on each flight. In the cloud cases, the variability is considerably larger than in the clear cases. This is expected due to greater variability in the cloud field and the corresponding decorrelation with the fixed surface measurements. As before, the leg-to-leg variability in the

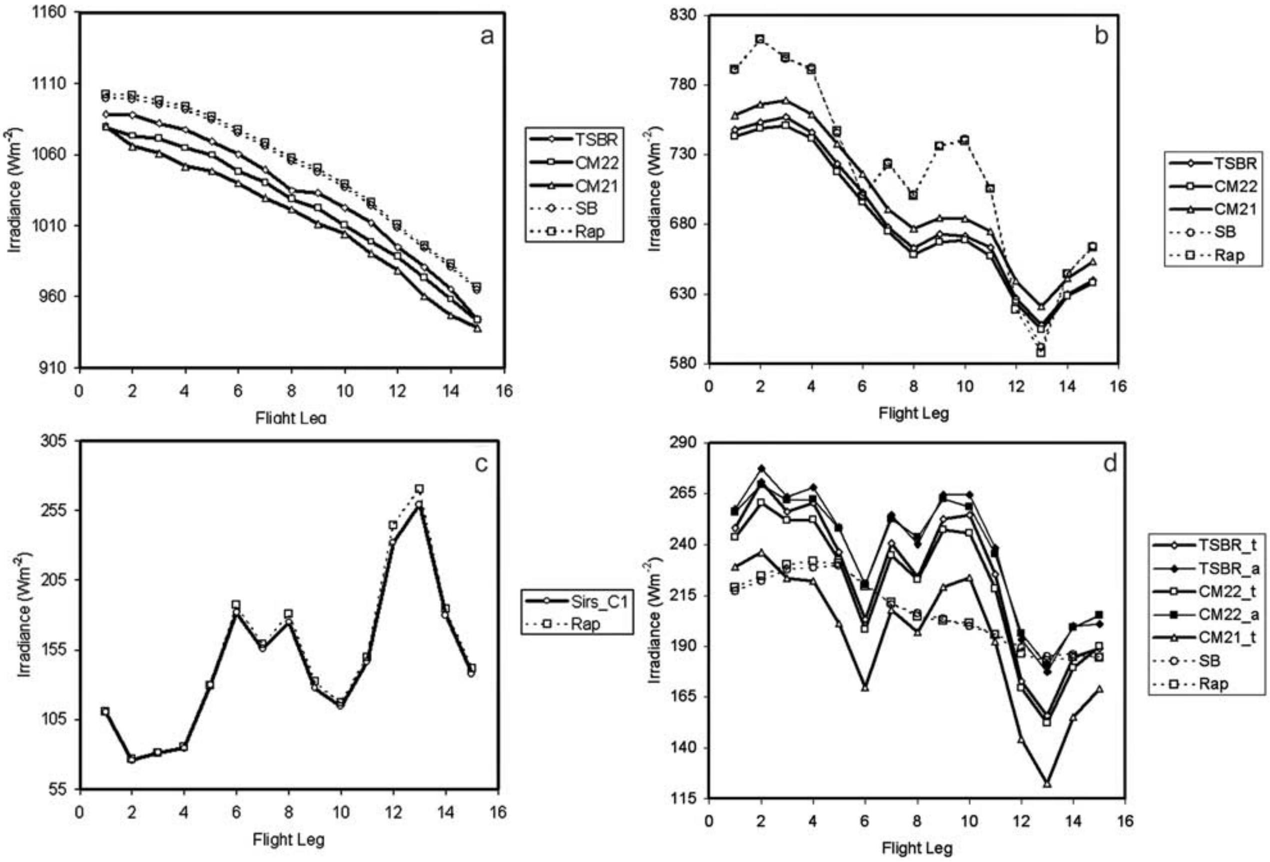

Figure 6. Comparison of measured and modeled quantities on 29 March, a cloud day. (a) Downward flux at 7 km. Legend identifies the three radiometers and the two models, which include no aerosol in these calculations. (b) Upward flux at 7 km. (c) Downward flux at the SGP central facility; only results from RAPRAD are shown because SBDART was constrained to match the downwelling flux exactly. (d) Measured layer absorption calculated using either the tower or aircraft albedo and model-calculated absorption using both RAPRAD and SBDART.

model absorption is less than that in the measurements because the model calculations do not suffer the spatial mismatch of the measurements between the aircraft and the fixed ground site.

[31] The 29 March case shows the largest difference between model and measurements and also has the largest variability. The downwelling flux at the Otter level (Figure 6a) has similar features to that shown in Figure 3a for 20 March. The model curves are smooth and close together, while the measurement curves show somewhat more variability and a definite offset from each other. The upwelling flux at the Otter level (Figure 6b) shows that the model curves are essentially identical and have a more pronounced variability than the measurements, which follow each other closely but with the CM21 offset from the other two. The measured fluxes are smoother because the hemispheric view of the radiometers integrates over a broad area of cloud with varying optical depth and associated reflectivity. The surface flux curve (Figure 6c) is the inverse of the upwelling flux because the sum of the cloud reflection and transmission for thick stratus is approximately constant. Note that we only show the comparison between RAPRAD and the SIRS data because the SBDART runs were constrained to match the SIRS data. The resultant absorption (Figure 6d) shows the model absorption decreasing smoothly but only slightly with decreasing optical depth. The measured absorption values track each other well (as they must, given the strong correlation evident in Figures 6a and 6b), but the CM21 results have a significant offset. On this day, the use of the aircraft albedo values produces an increase in absorption because they are higher than the corresponding 10-m-tower values.

[32] The fractional difference values (Figure 7) highlight the differences noted above. On 21 March, the differences are all less than 2–4%, which is well within any estimate of uncertainty. Some high cirrus were present on this day, but we took care to eliminate any legs of the daisy pattern in which the downwelling Otter flux measurements showed variability greater than 50 W m^{-2} or 5%. This criterion removed a little less than half of the total number of legs. The modeled and measured downwelling fluxes at the Otter for the remaining legs show no discernable discrepancy, so we are confident that no substantive high cloud was present about the aircraft for these legs. It is possible that some very thin veil of cirrus existed aloft, but it would have had to be much more horizontally uniform than is usually the case. In any case, such a thin veil would have very little impact on the solar radiation, other than increasing the diffuse field

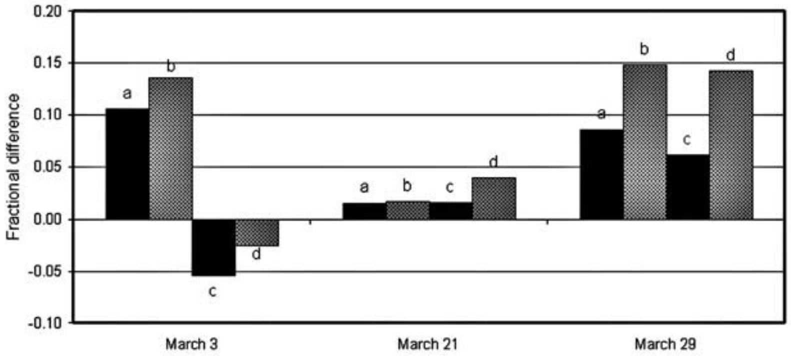

Figure 7. Same as Figure 4 but for the three cloudy days.

ever so slightly at the expense of the direct beam. Such a change would not affect the measured absorption in the underlying layer. The 3 March case shows a 2–5% difference for the CM22 depending on which albedo value is used, which again is well within reasonable levels of uncertainty. The TSBR values are between 10 and 14%, with the latter corresponding to the aircraft albedo. Because the difference between the TSBR and CM22 absorption exceeds the difference between the CM22 and computed absorption, it is difficult to argue that there is significant excess absorption on this day. The 29 March case shows a 6–8% difference if the 10-m-tower albedo is used and a 14% difference if the Otter albedo values are used. Because the total absorbed energy is about 220 W m^{-2}, the difference between the two different albedo cases is only about 15 W m^{-2}. Thus if we use the tower albedo, we would conclude that there is no significant excess absorption, while if we use the aircraft albedo, we would conclude that the results are significantly different.

[33] As we noted earlier, the aircraft albedo values exceed the tower albedo values on cloudy days, but the opposite is true on clear days. If the difference between the tower albedo and aircraft albedo values was simply due to spatial sampling, we would expect that difference to have the same sign on all days. The fact that the difference flips sign from clear to cloudy days suggests that there is some other effect going on. One plausible explanation for the difference is aerosol scattering. On the clear days, the boundary layer relative humidity (RH) was below 50%, while on all three cloudy days the boundary layer RH exceeded 80% everywhere and was at 100% below cloud base. Under these high RH conditions, aerosol particles grow in size and become much more efficient light scatterers. Since the aircraft measurements are made at a height of about 500 m, the effect of the aerosol is to increase the upwelling flux at the aircraft and thereby produce a larger albedo value. The values of the downwelling surface flux on 29 March (Figure 6c), for example, are on the order of 200 W m^{-2}. For a surface albedo of 16% (the tower value), this corresponds to an upwelling surface flux of 32 W m^{-2}. The TSBR albedo of 24% corresponds to an upwelling surface flux of 48 W m^{-2}. A layer of swollen aerosol particles between the ground and the aircraft is unlikely to account for the total difference of 16 W m^{-2}, but could certainly contribute a significant share of this difference.

[34] A second issue to consider is the accuracy of the flux measurements under these conditions. Broadband hemispheric radiometers are calibrated at flux levels on the order of 700–1000 W m^{-2}. *Ohmura et al.* [1998] claim an accuracy of 2 W m^{-2} for direct normal measurements and 5 W m^{-2} for diffuse measurements under the very best conditions. *Shi and Long* [2002] show that the disagreement between well-calibrated, colocated (separation of a few tens of meters) radiometers is at best about 6 W m^{-2} for direct normal and 4 W m^{-2} for diffuse measurements. Typical accuracies for well-maintained operational systems [*Shi and Long*, 2002] are on the order of 15 W m^{-2} or 3%, whichever is greater. During ARESE II, careful consideration was given to calibration of the ARM system [*Michalsky et al.*, 2002], resulting in a somewhat better absolute accuracy of perhaps 10 W m^{-2}. Since the upwelling fluxes being measured are only 30–50 W m^{-2}, an additional bias error of 10 W m^{-2} in one of the radiometer measurements can also account for much of the difference in the albedo values.

[35] One other possible explanation of the sign change is that the Otter only flew four legs below cloud to ascertain the albedo. If these four legs somehow sampled a different section of the site on clear versus cloudy days, then that could explain the shift in sign. We have looked at the spatially distributed albedo over the site using the detailed measurements available on the clear days and have found no compelling evidence of a sampling bias using only a few legs, so we discount this possibility.

[36] To a large extent, our interpretation of whether there is significant excess absorption hinges on the surface albedo values, particularly on the cloudy days. This is unfortunate because there is no clear way to decide whether we should use the local tower value or the aircraft value measured at 500 m. On 21 March, the tower and TSBR albedo values differ by less than 0.01 and the tower and CM22 values by only 0.03. It is interesting that the best agreement between measurements and models occurs on this same day on which the local and broadband albedo values are nearly identical. It is unclear whether this is a fortuitous result or is related to real difficulties in measuring the spatially distributed albedo.

4.3. Additional Sensitivity Tests

[37] One of the strengths of the ARESE II experiment design was the use of the instrumentation at the ARM

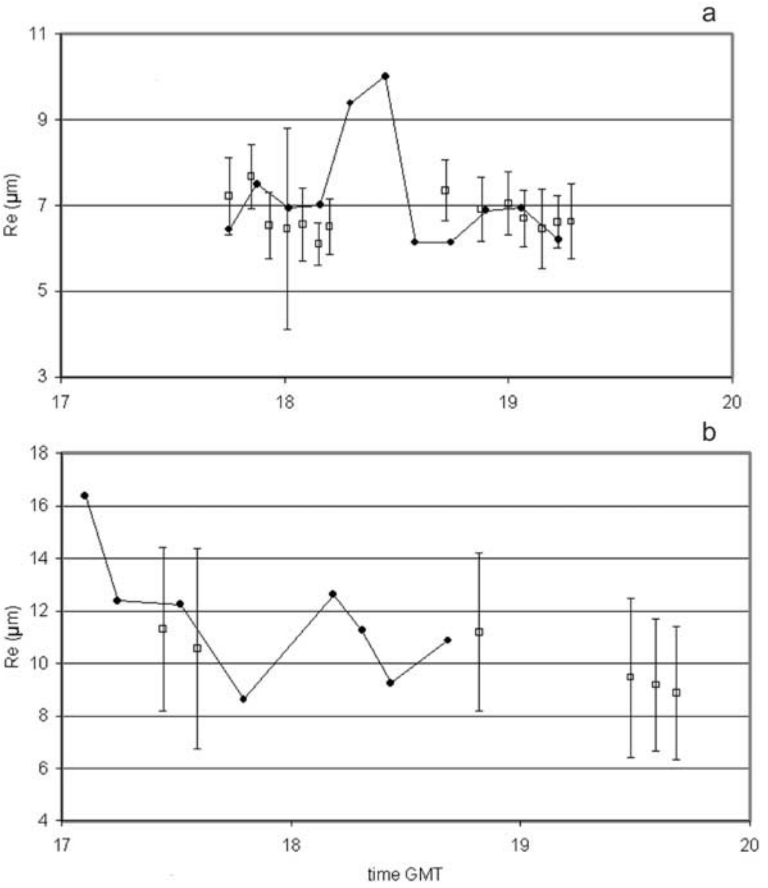

Figure 8. Comparison of model-constrained values of effective radius and measured values of effective radius. One model value (circles connected by a line) is obtained for each leg. The aircraft values are plotted as the mean and standard deviation of the values sampled in the cloud during the time period of that leg. Figure 8a hows the values for 3 March, and Figure 8b shows the values for 21 March. No aircraft data are available for 29 March.

central facility and the Citation to measure the cloud properties, and thereby constrain the model. As we described above, the Citation data are not uniform on all 3 days so we did not use them directly in our analysis. We can, however, use these data as a check on the particle sizes that we inferred by matching the surface flux (Figure 8). The model values of effective radius on 3 March agree very well with the measured values, except for legs 5 and 6. Unfortunately, we have no aircraft data at these exact times so we cannot tell whether the size distribution did indeed vary during this period. Both the measured and computed effective radius values are larger on 21 March than 3 March, but agree well with each other. Note that the computed values represent an effective radius for a size distribution that is constant with height in the cloud. The aircraft samples an actual cloud where mean size increases with distance from cloud base and the bars on the aircraft represent the standard deviation of the effective radius varying both horizontally and vertically. The fact that the two sets agree so well with each other is a strong indication that our approach of matching the model surface downwelling flux to the measurements is producing reasonable results. In a separate study, *Dong et al.* [2002] report on a comparison of cloud properties from aircraft, ground-based, and GOES retrievals for the March 2000 period. Their ground-based retrievals are also based on solar transmission but use a different approach and radiative transfer code. For 3 March, they report flight-average effective radius values of 6.3, 6.7, and 8.4 µm from the ground, aircraft, and GOES, respectively, and on 21 March, their values are 10.1, 9.6, and 9.4 µm, respectively. In both cases, these results are in very close agreement with ours.

[38] The good agreement evident in Figure 8 and the consistency with the results of *Dong et al.* [2002] provide a solid argument against the presence of significant anomalous absorption. Because we have constraints on the incoming solar radiation at the Otter level and the cloud liquid water path (LWP), the only free parameter in the model is the cloud-droplet-effective radius. If there were absorption occurring in the atmosphere that was not incorporated into our model, then matching the surface transmission would require a smaller effective radius in the model than was actually observed. The lack of small radius values in Table 3 indicates that this was not the case.

[39] We also considered the issue of drizzle drops within the clouds. The MWR records the total amount of liquid water in the cloud. In our calculations, we assume that this liquid water is all in the cloud drop-size distribution. This

Table 3. Cloudy-Sky Measured and Modeled Values of Absorptance (Abt) and Absorption (Abs)[a]

	March 3				March 21				March 29			
	Abt	SD	Abs	SD	Abt	SD	Abs	SD	Abt	SD	Abs	SD
TSBR tower	0.205	0.030	195	28	0.206	0.026	211	32	0.217	0.028	225	36
TSBR aircraft	0.211	0.028	200	27	0.207	0.027	211	32	0.230	0.024	238	32
CM22 tower	0.178	0.034	167	32	0.208	0.026	211	31	0.214	0.027	220	34
CM22 aircraft	0.184	0.033	172	31	0.212	0.025	216	30	0.231	0.022	237	29
CM21 tower	0.178	0.032	166	30	0.200	0.024	203	29	0.191	0.029	194	35
RAPRAD	0.182	0.006	174	7	0.203	0.006	209	6	0.197	0.010	207	18
SBDART	0.187	0.005	179	5	0.202	0.006	207	5	0.197	0.008	207	167

[a] The values are flight averages, and the standard deviations represent the leg-to-leg variability. Measured values are given for two different surface albedo values. Units are watts per square meter for the absorption and corresponding standard deviation.

was generally true on 3 March, but not on the other 2 days when we know that some drizzle drops were present. In cases in Table 3 where the model radius values are significantly larger that the measured values, we suspect that there is some amount of drizzle present. In order to investigate the impact of this drizzle, we added a 250-m layer of drizzle with an effective radius of 50 μm to the cloud at various levels within the cloud. When the drizzle layer is near cloud base, it actually decreases the column absorption by 1–2 W m^{-2} because moving some of the condensed water into the drizzle layer reduces the total optical depth of the cloud at solar wavelengths. Placing the drizzle at the very top of the cloud, which is clearly unrealistic physically, increases the absorption on the order of 10 W m^{-2} because the large drizzle drops absorb the solar radiation more effectively than the smaller cloud drops. Thus we conclude that drizzle is not a significant factor in altering the calculated absorption for these cases.

[40] As noted earlier, we can also determine the cloud particle size by matching the reflected radiation at the Otter. We did this in two ways, forcing our model to match either the TSBR-measured net flux or albedo. These two alternatives produce slightly different upwelling fluxes, but in both cases the cloud layer reflectivity has to decrease somewhat in order to match the observations. The absorption, however, basically remains unchanged. For the three cloud cases, the largest effect occurs on 29 March, where the effective radius increases by 1–1.5 μm, and the model absorption increases by 2–3 W m^{-2}. For a fixed LWP, the effective radius has to increase in order to increase the transmission, which in turn decreases the optical depth. The latter reduces the absorption and the former increases it slightly. The net effect is an approximate cancellation. Increasing or decreasing the LWP by 5% has about the same magnitude effect because it produces a similar magnitude change in the cloud optical depth.

[41] The one remaining issue is the treatment of aerosol in the cloudy-sky simulations. The model calculations for cloudy skies (Figures 5–7) contain no aerosol because we had no a priori information about aerosol loading under cloudy conditions. One might assume that the clouds reduce the aerosol loading by scavenging the aerosol, but absorbing particles in cloud drops can actually enhance absorption slightly. It is also possible that much of the absorbing aerosol exists interstitially in the cloud, which can also increase its absorption. In order to evaluate the effect of including aerosol in our calculations, we assumed that an aerosol profile existed on the cloudy day that was similar to that on adjacent clear days and that it was mixed interstitially with the cloud drops. We carried out several simulations for the 29 March case, testing both mineral and continental aerosol distributions with optical depths similar to those found on adjacent clear days. We found that the presence of aerosol increases the model absorption in these cases. For example, adding a mineral aerosol with an optical depth of 0.1 increases the absorption on 3 March by 15 W m^{-2} and on 29 March by 10 W m^{-2}. This additional absorption essentially removes all the discrepancy between the TSBR and the models on 3 March (although the model absorption is now higher than that of the CM22) and roughly half of the difference noted on 29 March, reducing it to about 7% of the total absorption. Note that the addition of the aerosol reduces the model transmission by some fraction of the absorption. For complete consistency, the cloud-effective radius should be retuned (to a slightly larger value) to again force a match between modeled and measured transmission. This process, however, is analogous to retuning to match the reflectance. The absorption remains largely unchanged and the compensation occurs between the transmission and reflectance. These simple aerosol tests suggest that a large fraction of the discrepancy between model and measurement can be explained with a modest amount of weakly absorbing aerosol.

5. Conclusions

[42] The ARESE II data set provides a unique opportunity to understand solar absorption in the atmosphere because of the combination of three sets of broadband solar radiometer mounted on the Twin Otter aircraft and the ground-based instruments at the ARM Southern Great Plains facility. We have analyzed the three sets of measurements taken on two clear-sky days and three cloudy days. The cloudy days were characterized by extended stratiform clouds comprising liquid water. We modeled the solar radiative transfer in each case using two models, RAPRAD and SBDART. These two models use similar numerical schemes but with quite different treatments of gaseous absorption.

[43] On the clear days, we can specify all of the inputs to the radiative transfer models with the exception of the aerosol type. The downwelling fluxes at the surface from the two models agree to within 10 W m^{-2} or about 1% of the incident flux, which coincidently is about the same difference produced by the use of either a mineral or average continental aerosol type. The calculated absorption in the atmospheric column between 0 and 7 km from the two models agrees to about 5% of the total absorption. From

this, we conclude that our calculated absorption is accurate to about 5% and depends most critically on the specified aerosol type.

[44] The measured absorption in the clear sky from the three radiometer pairs on the aircraft and the ARM measurements at the surface differs by as much as 25 W m^{-2}, with the CM21 value being noticeably lower. The TSBR and CM22 measurements differ by 5–10 W m^{-2}. Because we compute the reflected solar radiation at the surface by multiplying the downward surface radiation by the surface albedo, we find that the measured absorption is most sensitive to the specification of the surface albedo. Using either a value from the 10-m tower at the ARM site or average values from low-level flight legs on the Otter produces absorption differences as large as 10% of the absorption. For the clear-sky cases, we generally, but not in all cases, achieved better agreement with the calculated absorption using the Otter albedo values, which were lower than the SGP 10-m values.

[45] A second contributor to measurement uncertainty is the difficulty of obtaining accurate measurements of downwelling flux at the aircraft altitude. Figures 3a and 6a show both the variability and offsets in the radiometer measurements. The model calculations are almost identical and are very insensitive to any uncertainties in the model inputs, in part because the current stratospheric aerosol loading is so small. These results are also largely unaffected by current debates about the exact spectral distribution of the solar source function because these are broadband fluxes, which makes them most sensitive to the value of the solar constant. We know that the value of the solar constant is correct to better than 1% because the agreement between measured and modeled values of the direct normal flux at the surface on clear days is better than 1% [*Halthore et al.*, 1997]. Once again, we want to emphasize that the difference between the measurements is on the order of 1 or 2% of the incident flux, which is extremely good. We do see, however, a consistent bias where the measured fluxes are lower than the model. At this point, we have no explanation for this and are reluctant to claim significance for this bias because it is within the error of the observations. Unfortunately, an error of 1% in this measurement of downwelling flux translates to an error of 10 W m^{-2} in the flux and a similar error in the absorption. Because the clear-sky absorption is on the order of 100 W m^{-2} and both the model fluxes and the individual radiometer measurements are accurate to no better than 10 W m^{-2}, we conclude that differences between calculated and measured absorption on the order of or less than 10% are not significant. Hence in our opinion, the differences shown in Figure 4 are not significant.

[46] The results from the three cloudy days are more variable and thus more difficult to interpret. In these cases, if we assume that no aerosol is present, we can specify all the inputs to the model with the exception of the effective radius of the cloud drops. We arrived at values of the effective radius by adjusting the effective radius in the SBDART runs until the calculated downwelling solar flux at the surface agreed with the measured flux. The results from the two models are in very close agreement, differing by less than 5 W m^{-2} out of about 200 W m^{-2} or by less than 3%.

[47] The three measurements show considerable differences on the 3 days. The CM21 values are again consistently lower than the TSBR but agree reasonably well with the CM22 on 2 of the 3 days. On 21 March, the measured and calculated absorption agree very well with each other. Some questions have been raised about the data on this day because of the occasional presence of high cloud. We have screened the data to remove flight legs on which the downwelling solar radiation measured at 7 km exhibited unusual variability. If any high clouds existed during the remaining flight legs, their optical depth was very uniform and very small, because the calculated and measured downwelling radiation at 7 km agrees well. There is no reason to assume that such thin clouds, should they exist, would have any impact on the layer absorption below 7 km. On 3 March, there is good agreement between the CM22 and the calculated absorption, but the TSBR absorption is about 10–13% higher than the calculated absorption. On 29 March, both the TSBR and CM22 absorption values are 7–14% higher than the calculated absorption. The lower value corresponds to the use of the 10-m-tower albedo, while the larger corresponds to the use of the Otter albedo. For these cloudy-sky cases, we generally, but not in all cases, achieved better agreement with the calculated absorption using the SGP 10-m albedo values, which were lower than the Otter values. This is the converse of the clear-sky case. The differences using the 10-m albedo values are not significant according to our analysis, while those using the Otter albedo values probably are. The Otter values, calculated from two low-level flight legs, have the advantage of capturing some of the spatial variability of the site. However, they suffer from the issues of aircraft motion, aerosol scattering, and low absolute values. Given all these difficulties, we see no way of deciding which set of albedo values is more accurate. Any future experiments directed at this problem of solar absorption, especially over land, must find a way of improving our knowledge of the solar albedo, including its spectral variations.

[48] We carried out a number of additional calculations in order to investigate the effects of various model inputs and assumptions on the column absorption. The only way in which we could significantly impact the calculated absorption was by the inclusion of aerosol. When we include a mineral aerosol with an optical depth of 0.1, the column absorption increases by 5–10%. This would reduce the differences shown in Figure 7 to 10% or less in all cases. On this basis, we conclude that the measured absorption in the three ARESE II cloudy-sky cases agrees with the calculated absorption to within the uncertainty of the measurements and calculations, including the uncertainty introduced by the lack of any aerosol information on the cloudy days.

[49] The one free parameter in our cloud model calculations was the cloud-droplet-effective radius. We chose to adjust this effective radius value until the calculated transmitted solar radiation matched the observed. We repeated this calculation using the reflected radiation as measured at the Twin Otter. We found little difference between the two approaches. In addition, we found that our model effective radius values agreed very well with in situ aircraft observations, as well as values from GOES and ground-based retrievals published by *Dong et al.* [2002]. These results alone can be used to argue against the presence of any

significant anomalous absorption. If significant absorption occurred in the atmosphere that was not present in the model, it would not be possible to get simultaneous agreement with both transmitted and reflected flux using the same effective radius, nor would it be possible to match in situ observations.

[50] Because we find no significant discrepancy in the ARESE II data between measurement and theory but such discrepancies have been reported elsewhere, it is worth considering what some of the differences may be between this data set and analysis and previous studies. First of all, we have used two state-of-the-art radiative transfer models. Some of the previous studies used more approximate models that tend to underestimate atmospheric absorption due to incomplete treatment of gaseous absorption. Radiation code comparison studies have demonstrated the weaknesses of some of these codes, but they continue to be used. The radiative transfer community has carried out a significant number of comparison tests and these results are readily available [e.g., *Barker et al.*, 2003]. The broader atmospheric science community should take these comparisons seriously and use the models that are demonstrated to be of high accuracy, especially when trying to compare theory with measurements. As we have shown, these models agree with clear-sky absorption measurements to the accuracy of the measurements and the knowledge of the input aerosol properties. Second, the ARESE II data set is unique in its redundant set of broadband measurements, which allows us to assess the uncertainty in the measured absorption values. The data set also is unique in the focus on obtaining cloud properties in addition to fluxes. This reduces the uncertainty in the model inputs, which in turn constrains the calculated absorption. This combination of a detailed, high quality data set and state-of-the-art radiative transfer models has allowed us to carry out detailed case comparisons and demonstrate their fundamental agreement.

[51] The studies of *Cess et al.* [1995] and *Ramanathan et al.* [1995] suggested that measured atmospheric absorption in cloudy skies exceeds calculated absorption by 40% or more averaged over all types of clouds. *Pilewskie and Valero* [1995] supported this claim based on observations in tropical cirrus conditions, while *Valero et al.* [1997] claimed even greater absorption based on measurements in continental stratus conditions. Discrepancies as large as these cannot be explained by any reasonable extensions of current radiative transfer models or modifications of model inputs. Consequently, these papers generated considerable speculation about unidentified physical processes that might produce absorption in and around clouds. The ARESE II experiment provides a considerably more complete data set than previous experiments. Our analysis shows no disagreements larger than 14% and we conclude that the measured absorption is only accurate to 10% "at best." Thus any disagreement between model and measurement can be bracketed by some combination of measurement uncertainty analysis and uncertainty in the inputs of surface albedo and aerosol properties. Therefore interpreting these current results from ARESE II certainly does not require the invocation of any extraordinary physics. While it is difficult to disprove the results of previous studies with the results of this current experiment, or to generalize from one cloud type to all cloud types, it is our opinion that the ARESE II results provide compelling evidence that it is time for the atmospheric science community to lay to rest these discussions of extreme solar absorption in cloudy atmospheric columns.

[52] **Acknowledgments.** The research presented here draws on a broad spectrum of data collected by many different people. We are indebted to all these individuals for their dedication and effort. We want to thank particularly Robert Ellingson, the Chief Scientist for ARESE II, for his effort in making ARESE II a success, and Francisco Valero, Shoji Asano, and Tim Tooman and their associates for providing the aircraft radiometer data for this study. We also wish to thank the staff at the ARM Southern Great Plains facility for providing the surface data. We are indebted to Chuck Long for many helpful discussions, particularly regarding radiometer performance and accuracy. We appreciate the efforts of the journal reviewers; their comments significantly improved this paper. This research was supported by the Office of Biological and Environmental Research (OBER) of the U.S. Department of Energy under contract DE-AC06-76RL01830 as part of the Atmospheric Radiation Measurement Program. We think it appropriate also to acknowledge the long-standing interest of Ari Patrinos, Associate Director of OBER, in this problem. Without his support, ARESE and ARESE II would not have occurred.

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