Solar Radiation Budget from the MRI Radiometers for Clear and Cloudy Air Columns within ARESE II

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ABSTRACT

As an international collaborative research activity within the Japanese Cloud-Climate Study (JACCS) program, the authors participated in the second Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE II) using the Meteorological Research Institute (MRI) radiometers. This paper describes results of ARESE II, as well as specifications and calibration of the MRI radiometers. The solar radiation budget for 2 days of typical clear sky (27 February and 20 March 2000) and overcast sky (3 and 21 March 2000) has been analyzed using spatially collocated, total-band solar irradiances measured by the MRI pyranometers (Kipp & Zonen CM21). These were installed on a Twin Otter aircraft, and deployed at the ARM Southern Great Plains Central Facility site. On average, the clear-sky and overcast-sky air columns between the surface and the Twin Otter flight level of 7 km absorbed about 13% ± 2% and 20% ± 3%, respectively, of the total-band solar radiation incident on the column top. The measured solar radiation budgets agree well with those computed for models of clear and cloudy atmospheres. The present results indicate no evidence of anomalous solar absorption for either the clear- or cloudy-sky cases. It is suggested that about half of the observed absorption enhancement of 7% for the overcast-sky cases could be caused by the presence of larger water vapor, compared with the clear-sky cases, and that the other half could be caused by increased absorption within and above the rather low cloud layers.

1. Introduction

During the past several decades, there has been considerable confusion and controversy as to how much solar radiation clouds actually absorb. It has been frequently reported that the measured solar absorption in cloudy atmospheres greatly exceeded that measured for cloudless atmospheres and/or theoretically predicted values (see, e.g., Cess et al. 1995; Ramanathan et al. 1995; Pilewskie and Valero 1995; Valero et al. 1997). These events have often been called enhanced cloud absorption or the cloud absorption anomaly (e.g., Stephens and Tsay 1990; Li et al. 1995; Stephens 1996).

Two experiments done in the late 1990s, using similar observational strategies with two collocated aircraft, reported conflicting results concerning the existence of anomalous solar absorption. The Atmospheric Radiation Measurement (ARM) program, supported by the U.S. Department of Energy, operated an intensive field experiment called the ARM Enhanced Shortwave Experiment (ARESE) over the Southern Great Plains (SGP) site in Oklahoma in 1995. Papers based on the ARESE aircraft data by Valero et al. (1997) and Zender et al. (1997) claimed significant evidence of excess solar absorption in cloudy atmospheres, but not in clear-sky cases. However, Li et al. (1999), using some of the same ARESE data as well as other satellite and surface data, found no evidence of excess absorption for the same cloudy cases. Later, Valero et al. (2000) reanalyzed the ARESE data, including simultaneous satellite and surface data for several cloudy cases, and they again obtained evidence of excess solar absorption by cloudy atmospheres when compared with model estimates.

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Thus, the ARESE could not clearly resolve the question of cloud anomalous absorption, and the second ARM Enhanced Shortwave Experiment (ARESE II) was initiated. The Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA) had also conducted intensive airborne cloud–radiation experiments as part of the Japanese Cloud–Climate Study (JACCS) program undertaken during FY1991 through FY1999. This was one of the Japanese climate research efforts focusing on issues related to cloud and radiation interactions (Asano et al. 1994). From analysis of the JACCS experimental data, Asano et al. (2000, 2002) found no evidence of anomalous solar absorption for stratocumulus clouds observed over the sea around Japan.

To resolve the discrepancy between the ARESE and JACCS results, we were invited to participate in ARESE II using the same radiometers as used in the previous JACCS experiments. The observational strategy of ARESE II (Ellingson and Tooman 1999) was different from the stacked two-aircraft strategy used in both the ARESE and JACCS experiments. The ARESE II strategy used only one Twin Otter (TO) aircraft repeatedly flying a daisy pattern over the ground-based observation site at the SGP Cloud and Radiation Testbed (CART) central facility (CF) (Stokes and Schwartz 1994). On the Twin Otter we installed the pair of broadband pyranometers (Kipp & Zonen CM21) that were used in the JACCS aircraft experiment. The TO aircraft was also equipped with two other sets of broadband shortwave radiometers: the Kipp & Zonen CM22 pyranometers from Sandia National Laboratories (SNL) and total solar broadband radiometers (TSBR), developed by Valero et al. (1982), from the Scripps Institution of Oceanography (SIO). Thus, ARESE II provided a good opportunity to investigate the effects of different radiometers on measurements of solar absorption by clouds. At the ground site, we deployed the same kind of pyranometers for measuring solar irradiances. In this paper, we present a description of the experimental JACCS/MRI research effort within ARESE II, and discuss the results obtained using the MRI radiometers. The observational results from different radiometers are compared and discussed in detail by other investigators (e.g., Ackerman et al. 2003; Oreopoulos et al. 2003; Valero et al. 2003; O’Hirok and Gautier 2003).

2. MRI radiometers

a. Instrumentation

We used several Kipp & Zonen CM21 pyranometers for measuring the broadband solar irradiances. One CM21 pyranometer was installed on the top of the TO fuselage and the other on the bottom of the fuselage, for airborne measurement of the downward and upward total-band (0.3–2.9 µm) solar irradiances, respectively. Output signals of the airborne pyranometers were digitized and recorded on the common TO data acquisition system. Further, we deployed several solar radiometers at the CART facility site located at 36.59°N, 97.48°W. A ventilated CM21 pyranometer for measuring the downward total-band solar irradiance was installed on the roof of a trailer at the site. A six-channel sun photometer (EKO M-115) and a total-band pyrheliometer (Kipp & Zonen CH-1) were mounted on an automatic sun tracker (Prede Co. ASTX-1). The sun photometer was used to measure optical thicknesses of aerosols at wavelengths of 368, 420, 500, 675, 862, and 1050 nm. We also mounted another ventilated CM21 pyranometer on the top of the same sun tracker for measuring the diffuse irradiance: the sun tracker had a shadowing disk to block the direct normal solar radiation. A downward-looking CM21 pyranometer was installed on a 1.5-m-high stand to measure the upwelling radiation reflected from the ground surface. In this analysis, however, we have not used the upwelling radiation data to evaluate the surface albedo of the area because surface inhomogeneity may seriously affect the surface albedo of the SGP CART site area (Li et al. 2002).

The analog output signals from the MRI surface radiometers were converted to 16-bit digital data by a multichannel analog/digital converter (ETO DENKI Co. THERMODAC-EF) and saved as ASCII files in a personal computer at 10-s intervals. The MRI ground-based measuring system was operated by unmanned computer control with support by the instrument maintenance staff at the CART site. The surface radiation data were sampled every 10 s from 0600 to 0900 LT during the experiment period; however, the MRI ground-based measurement ended on the evening of 27 March 2000. Unfortunately, the MRI ground-based data acquisition system suffered irregular pulselike noise due to electromagnetic interferences, the cause of which we could not identify. We have tried to filter out the electronic noise as much as possible for cloudless cases. We also removed evidently noisy data by eye, from the original records for the two cloudy cases analyzed here. It should be noted that any noise reduction had not been applied to the 1-min-averaged, MRI surface radiation data of cloudy cases archived in the ARM ARESE II dataset, and it is suggested by Michalsky et al. (2002) that the archived MRI surface CM21 data might be biased by as much as 10 W m$^{-2}$ for cloudy cases. In this study, we did not use the 1-min-averaged ARM ARESE II dataset, but we have reprocessed the original surface radiation data to remove the pulselike noise, and this substantially reduced the bias for the two cloudy cases.

b. Calibration of MRI radiometers

1) CM21 ON TWIN OTTER

The MRI CM21 pyranometers installed on the TO were calibrated by a ground-based comparison against reference solar radiation data obtained by the University of Albany, State University of New York (SUNY)
group. This was done before (16 February) and after (8 April) the research flight series at Blackwell–Tonkawa airport. The method and accuracy of the calibration are discussed in detail by Michalsky et al. (2002). Unfortunately, in the calibration campaign, almost all of the participating radiometers were misaligned from the horizontal by different amounts. For the SNL CM22 and SIO TSBR, the misalignment was less serious on 16 February than on 8 April. The calibration constants of these radiometers were determined by comparing the data obtained during a clear-sky time interval around local noon 16 February with the corresponding SUNY reference data: the preflight calibration constants were expected to satisfy accuracy requirements throughout the entire experiment (Michalsky et al. 2002). However, the leveling error introduced a systematic bias as large as 10 W m$^{-2}$ in the diurnal variations of the clear-sky surface irradiances measured by these radiometers, as seen from Figs. 6 and 7 of Michalsky et al. (2002). We have corrected the misalignment of the CM21 pyranometers by estimating the inclination angles of the pyranometer plane from the horizon. The correction procedure is described in the appendix. To do the comparison, we used the available data for as long a period as possible between 0900 and 1600 local time (LT) during which time most of research flights were carried out. Figure 1 demonstrates the effects of data intervals used for calibration and misalignment correction. It shows that the short-term comparison using only 1-h data in the morning or evening of 8 April is not sufficient to accurately recover the diurnal variation of the reference solar irradiance. The calibration constants thus determined via the comparisons on 16 February and 8 April were then averaged with weightings of one to two for their calibration constants, respectively. We gave the larger weighting to the calibration constant determined from the comparison on 8 April because for the 16 February case we were unable to uniquely determine the misalignment angle for the shorter period of clear-sky conditions on that day. The weighted-mean calibration constant has been used in processing the MRI CM21 airborne data obtained in the ARESE II campaign.

2) Ground-based radiometers at CART site

The total-band CM21 pyranometers and CH-1 pyrheliometer were calibrated by comparison with the corresponding SUNY surface radiation data. The calibration constants of the CM21 pyranometers were determined from the mean of comparisons done on 4 days: 16 February at the Blackwell–Tonkawa airport and 27 February, 4 March, and 27 March at the CART CF site. The standard deviation of the calibration constants over the 4 days was 1.0% of the mean value. The largest deviation was for the calibration constant determined from the data obtained on 16 February, for which the CM21 was misaligned, as stated above. For the CH-1 pyrheliometer, the calibration constant was determined as the mean of comparisons on 3 days: 27 February, 4 March, and 27 March at the CART CF site. For the calibration on 16 February, we compared the available data for as long period as possible to correct for the leveling misalignment of the CM21 pyranometers, as discussed above. The clear-sky, global solar irradiance measured by this calibrated CM21 pyranometer generally agreed with the SUNY reference irradiance within
c. Corrections

(1) TEMPERATURE DEPENDENCE

It is well known that broadband pyranometers using thermopile detectors suffer measurement errors and biases due to temperature dependence, cosine-law response and the so-called thermal offset (or zero offset). During the TO flights, the airborne pyranometers may suffer large changes of body temperatures. The zenith-looking and nadir-looking CM21 pyranometers were each mounted in the head of the top and bottom fairings, respectively, which were attached to the external surface of the aircraft fuselage. The pyranometers were thermally insulated from the mount bases using phenolic adapters. Open air was allowed to circulate around the body of the pyranometers [J. S. Smith (of SNL) 2002, personal communication]. Therefore, because of the strong ventilation during level flights at any altitude, the body and dome temperatures of the pyranometers would be expected to be close to the outer air temperature at that altitude. This situation was similar to the case of the JACCS aircraft experiments (Asano et al. 2000, 2002).

Each CM21 pyranometer has its own temperature dependence. Figure 2 shows the temperature dependence of the pyranometers installed on the TO. The laboratory-measured temperature dependence (normalized at 20°C) was approximated by a quadratic equation, shown by the solid and broken lines. From the quadratic expressions and using the measured air temperature, we normalized the outputs of the zenith-looking and nadir-looking pyranometers to a reference temperature of 10°C. The magnitude of the corrections were less than 0.3% for the zenith-looking and nadir-looking CM21s, respectively, for the temperatures encountered in the ARESE II flights. For the ground-based pyranometers, a similar correction for temperature dependence was applied to normalize their outputs to a reference temperature of 10°C. The magnitude of the correction was less than 0.3%.

(2) THERMAL OFFSET

The thermal offset is caused by the temperature difference ($\Delta T_c$) between the (inner if double) glass dome and the detector surface with pyranometer temperature ($T_p$), and it is proportional to $\sigma T_p^2 \Delta T_c$, where $\sigma$ is the Stefan–Boltzmann constant (Asano et al. 2000). Recently, quite large thermal-offset biases, sometimes exceeding 10 W m$^{-2}$, have been reported for several Eppley Precision Spectral Pyranometers (PSPs) (Ji and Tsay 2000; Bush et al. 2000; Haeffelin et al. 2001). Haeffelin et al. (2001) and Dutton et al. (2001) showed that clear-sky daytime biases could be larger, as much as double, than the nighttime values for the diffuse irradiances measured by a few PSPs. In addition, Dutton et al. (2001) suggested an effectiveness of forced ventilation systems to reduce nighttime and daytime offsets, and they also suggested that daytime offsets of even unventilated CM21 pyranometers could be less sensitive to net thermal infrared exchanges between the detector and domes than those of the ventilated PSPs. Actually, we found much smaller nighttime negative outputs of 2 to 3 W m$^{-2}$ for the ventilated CM21 pyranometers used at the CART CF site. Any further quantitative feature of daytime offsets of CM21-type pyranometers is not available at present. In this study, we suppose that daytime offsets of the surface CM21 pyranometers might be not larger than 5 W m$^{-2}$. For the airborne CM21 pyranometers, errors due to the thermal offset might be negligibly small during the level flight observations because the body and dome temperature difference $\Delta T_c$ could be quite small owing to the strong ventilation effects mentioned above. This is indirectly supported by the good agreement between the airborne-measured irradiances by the MRI CM21 and the SNL CM22 pyranometers (Oreopoulos et al. 2003); the latter CM22 pyranometer is the newest Kipp & Zonen model which is said to have smaller thermal offsets.

(3) COSINE-LAW RESPONSE

Figure 3 shows the laboratory-measured cosine-law responses for the TO zenith-looking CM21 and the ground-based CM21 used to measure the total-band global irradiance. By neglecting the azimuth angle dependence of the cosine response, and using the mean zenith-angle dependence averaged over four azimuthal
directions, we corrected the outputs obtained at different solar zenith angles. The correction was applied only to the direct components of the global irradiance ($G$) under the assumption that the diffuse component ($D$) is isotropic, and the diffuse to global irradiance ratio ($D/G$) is known. For the TO zenith-looking CM21 during level flights at about 7 km, the $D/G$ ratio was assumed to be 0.05 for cases without high cirrus clouds. The solar zenith angle at each sampling time was calculated from the TO navigation data. For the surface global irradiance measurement, the $D/G$ ratio was estimated from the pyranometer measurements of the global and diffuse irradiances. The magnitude of the cosine-response correction was less than 0.5% for zenith angles smaller than 75°. For the TO nadir-looking CM21 and the surface CM21s for measuring diffuse irradiances, we neglected their cosine-response effects.

4) Aircraft fluctuations

For airborne measurements of the horizontal solar irradiance, the most serious problem is caused by aircraft attitude fluctuations. It is usually difficult for conventional pyranometers to be installed exactly parallel to the reference axis of the aircraft navigation system. Usually, the pyranometer alignment suffers biases in pitch and roll angles measured by the navigation system. Outputs of the TO zenith-looking CM21 were corrected for tilts of the pyranometer plane due to aircraft attitude fluctuations by a method similar to that used by Asano et al. (2000, 2002). When applying the attitude correction, the pyranometer misalignment with respect to the reference axes was adjusted so that the downward solar irradiances measured on the TO, flying at different headings at the same altitude under clear-sky conditions, did not contain discontinuities due to changes in the heading (Bannehr and Schwiesow 1993; Asano et al. 2000). Biases (pitch and roll) with respect to the TO reference axes were estimated to be $(+2.5°, 0.0°)$ for the flights from 24 February to 5 March, $(+0.6°, −0.2°)$ for the flights from 9 March to 21 March, and $(+2.5°, 0.0°)$ for the flights from 29 March to 5 April. The airborne pyranometers were removed and reset approximately every two weeks when the silica gel (drier) was renewed. No corrections for attitude fluctuations have been applied to the upward irradiances measured by the TO nadir-looking CM21.

The overall accuracy of the solar irradiance measurements by the CM21 pyranometers were limited by various uncertainties involved in the aforementioned calibrations and corrections, as well as by some unexpected sporadic noises; however, it was estimated to be generally better than 20 W m$^{-2}$ throughout the ARESE II period.

3. Analysis of the observed data

a. Radiative properties of the air column

We have evaluated the radiative properties such as reflectance (albedo), transmittance, and absorptance of the air column between the aircraft flight level and the surface. Similar to Asano et al. (2000, 2002), we define reflectance $R$ as the ratio of the upward to downward irradiances measured on the TO, and transmittance $T$ as the ratio of the surface net (downward − upward) irradiance to the TO downward irradiance. If the absorptance $A$ is defined as the net convergence in the air column divided by the TO downward irradiance, then $R$, $T$, and $A$ satisfy the relationship $R + T + A = 1$. We measured the surface reflected irradiance by the downward-looking CM21 mounted on the 1.5-m-high stand at the SGP CF site; however, this pyranometer malfunctioned after 18 March. Furthermore, the point-based measurement of upward irradiance reflected from the surface may not necessarily represent the mean irradiance reflected from the larger-area SGP site, which has heterogeneous surface properties (Li et al. 2002). So, we calculated the surface upward irradiance from the downward surface global irradiance measured by the total-band CM21 pyranometer, multiplied by the sur-
face albedos measured by the airborne CM21s during the low-altitude albedo runs (about 150 m above the ground level). The albedo runs were flown over the CART site before and/or after the high-altitude data-collection runs. Because the solar zenith-angle dependence of the measured surface albedo was quite small, we neglected the effect of the time difference between albedo runs and data-collection runs. The point-based surface albedo and the airborne-measured surface albedo were almost identical for the clear-sky case of 27 February. However, Michalsky et al. (2002) suggested that the surface albedo measurements by airborne MRI CM21 pyranometers were overestimated by 0.01 to 0.02 when compared with those measured by the SNL CM22s and SIO TSBR. The effect of overestimating the surface albedo, $\alpha_s + \Delta \alpha_s$, by an amount $\Delta \alpha_s(\geq 0)$ may yield a slight underestimate in the transmittance $T$ and a slight overestimate in the absorptance $A$, according to $T \Delta \alpha_s / (1 - \alpha_s)$. This can amount to at most 0.005 for cloudy cases with $T \leq 0.2$ and $\alpha_s \approx 0.02$. For a mean TO downward irradiance of about 950 W m$^{-2}$ at the air-column top, the accuracy of the total-band absorptance measurement was estimated to be at worst $\pm 0.03$, considering the uncertainty of about $\pm 20$ W m$^{-2}$ in the irradiance measurements, as well as uncertainties in the surface albedo estimate.

b. Data sampling

Using the total-band solar irradiances measured by the CM21 pyranometers, we have analyzed radiation budgets of the air column between the surface and the TO flight level at about 7 km. On the TO, the CM21 output data were collected at a 10-Hz sampling rate, and averaged over 1-s intervals. On the other hand, the MRI surface radiation data were sampled every 10 s. We matched the time resolution of the aircraft and surface data in the analysis by taking 10-s means of the aircraft data.

The instantaneous absorptance values obtained from the above definition by using simultaneous TO and surface irradiance data do not represent true absorptance, except for the cases of horizontally homogeneous atmospheres, because those data are not, in general, spatially collocated except when the TO flew directly over the ground site. Further, for horizontally inhomogeneous atmospheres, there is often significant net horizontal transport of photons into or out of an air column, even when collocated perfectly, which may bring an apparent column absorptance (Marshak et al. 1999; Asano et al. 2000). Assuming that during the TO observation flights clouds move over the ground site and that the solar zenith angle does not change greatly, grand averaging over a long enough time and/or flight distance (for the TO data) may largely cancel the effects of horizontal inhomogeneity and lead to a reliable estimate of the column absorptance for cases where horizontal cloud inhomogeneity is not too great or randomly or periodically distributed. However, this may not be necessarily valid even for grand averaged cases where cloud fields have systematic spatial structures. To reduce the effects of net horizontal transport of photons in their ARESE II data analysis, Oreopoulos et al. (2003) used the conditional sampling proposed by Marshak et al. (1999), and selected only the broadband absorptance values at instants when the apparent absorptance at a visible narrowband was close to its presumed value.

In this study, to match approximately the effective field of view of the TO nadir-looking CM21 and the ground-based zenith-looking CM21 and to sample the irradiance data collocated in time and space, we selected only data for which the TO flew within an area of a radius of 1.2 km from directly overhead of the ground site (3 March), and of 2 km (21 March) for the cloudy cases and a radius of 3.5 km for the clear-sky cases. Depicted by darker points in Fig. 4 is an example of the collocated data sampling, in the central part of the TO daisy tracks flown on 20 March. We used mainly the sampled data to analyze the radiation budget. For comparison, we also used data obtained during the full time intervals of data-collection runs, except when the aircraft turned at the outer edges of the flight pattern and the rolling and/or pitching angles exceeded 10°. Hereafter, we call the latter data the full-time-series data. In Table 1, we compare the radiative properties estimated from the sampled data and the full-time-series data for both clear and cloudy air columns.

c. Results of radiation budget analysis

1) Clear-sky cases

We have analyzed the total-band solar irradiance data measured by the CM21 pyranometers for two cases of...
Table 1. Comparison of the measured and calculated radiative properties for the air columns under clear-sky conditions (27 Feb and 20 Mar) and overcast-sky conditions (3 and 21 Mar).

<table>
<thead>
<tr>
<th></th>
<th>Clear</th>
<th>Cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27 Feb</td>
<td>20 Mar</td>
</tr>
<tr>
<td>Number of data</td>
<td>Sampled</td>
<td>Full-time series</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>650</td>
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<tr>
<td>Reflectance:</td>
<td>measured; sampled</td>
<td>[Calculated]</td>
</tr>
<tr>
<td></td>
<td>0.206</td>
<td>0.210</td>
</tr>
<tr>
<td></td>
<td>(0.179)</td>
<td>(0.183)</td>
</tr>
<tr>
<td>Transmittance:</td>
<td>measured; sampled</td>
<td>[Calculated]</td>
</tr>
<tr>
<td></td>
<td>0.674</td>
<td>0.674</td>
</tr>
<tr>
<td></td>
<td>(0.680)</td>
<td>(0.680)</td>
</tr>
<tr>
<td>Absorptance:</td>
<td>measured; sampled</td>
<td>[Calculated]</td>
</tr>
<tr>
<td></td>
<td>0.120</td>
<td>0.121</td>
</tr>
<tr>
<td></td>
<td>(0.141)</td>
<td>(0.138)</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>measured; sampled</td>
<td>[Calculated]</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>0.22</td>
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<tr>
<td>Solar zenith angle</td>
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<td>[Calculated]</td>
</tr>
<tr>
<td></td>
<td>47.1</td>
<td>47.1</td>
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<tr>
<td>Aerosol:</td>
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<td></td>
<td>Dustlike</td>
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<td></td>
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<td>Cloud:</td>
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</tr>
<tr>
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<tr>
<td></td>
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<td>25</td>
</tr>
<tr>
<td></td>
<td>R (μm)</td>
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<tr>
<td>Water vapor amount (g cm⁻²)</td>
<td>0.642</td>
<td>9.27</td>
</tr>
</tbody>
</table>

a Measured value averaged over the sampled data.
b Measured value averaged over the full-time series data.
c Surface albedo measured by the airborne CM21 pyranometers during the TO albedo runs about 150 m above the ground.
d Mean solar zenith angle during the time interval of data collection.
e Aerosol optical thickness: for the clear cases, the sun-photometer-measured total optical thickness is equally partitioned to dustlike and water-soluble particles; for the cloudy cases, the optical thicknesses are assumed.
f Cloud-top and -base heights (MSL) estimated from the ceilometer measurements at the CART CF site and the UND Cessna Citation measurements in the ARM Spring 2000 Cloud IOP.
g Cloud optical thickness was tuned to fit the computed reflectances to the measured ones.
h Effective cloud-particle radius estimated from the FSSP data in the ARM Spring 2000 cloud IOP.
i Precipitable water vapor amount, in the entire atmospheric columns, estimated from the ARM MWR measurements at the CART CF site.

Typical clear-sky (27 February and 20 March) and overcast-sky (3 and 21 March) conditions. Figure 5a shows the time series of the upward and downward irradiances measured on the TO and at the surface for the clear-sky case of 27 February. The irradiances change smoothly with time except for small fluctuations in the TO downward irradiance, which may partly result from insufficient corrections for aircraft attitude fluctuations. For the clear-sky case, although the TO upward irradiance is only slightly larger than the surface upward irradiance, with differences less than 15 W m⁻², there are much larger systematic differences exceeding 100 W m⁻² between the downward irradiances measured on the TO and at the surface. This means that there was substantial convergence (absorption) of the total-band solar radiation in the air column. To evaluate the radiation budget of the air column, we used the sampled data collocated in time and space; these data are indicated by the darker points on each irradiance curve. Figure 5b shows the corresponding time series of the radiative properties \( R, T, \) and \( A \) for the air column on 27 February. In the figure, for reference, we plotted the full-time-series variations of the radiative properties that were evaluated from the simultaneous irradiance data measured on the TO during level flights and data measured at the surface, even though the data were not necessarily collocated in space. The full-time and sampled plots agree very well, as also shown in Table 1. This suggests that the clear-sky atmosphere was horizontally uniform and steady with almost constant radiative properties during the 2-h observation period. The air column absorbed about 12% of the total-band solar radiation incident on the top of the 7-km-high air column. Figure 6 shows a similar time series of the downward and upward irradiances, and the radiative properties for another clear-sky case on 20 March. The air column of this case seems a little more absorptive, compared with the former 27 February case, with a slightly greater absorptance \( A \) of 14% and a slightly reduced reflectance \( R \).

2) OVERCAST-SKY CASES

The corresponding figures for the measured irradiances and the estimated radiative properties for the
cloudy cases of 3 and 21 March are shown in Figs. 7 and 8, respectively. The TO downward irradiance on 21 March, shown in Fig. 8a, exhibits significant fluctuations caused by the effects of upper cirrus clouds. For the two cloudy cases, the TO upward irradiance and the surface irradiances fluctuate with various amplitudes and time scales. This reveals spatial inhomogeneity of the cloud layers moving over the CART CF site. Although there were time variations in the irradiances and radiative properties, the figures show that the sampled data generally follow the full-time series fluctuations, having values within the range of the full-time series variations. As seen from the relatively large changes in reflectance \( R \) and transmittance \( T \), the optical and/or geometrical thickness of the cloud layers gradually changed during the 2-h observation period. We divided the period into a few intervals with rather uniform radiative properties, as indicated by arrows in Figs. 7b and 8b. In Table 1 we have summarized the radiative properties evaluated for the cloudy air column in each time interval. Although the averaged cloud absorptances estimated from the sampled data are slightly smaller than those estimated from the full-time series data, the differences are too small (\( \leq 0.01 \)) to further discuss the effects of cloud inhomogeneity on the data sampling for the present cases. On the case average, the clear-sky and overcast-sky air columns absorbed about 13% and 20%, respectively, of the total-band solar radiation incident at the TO flight level of 7 km.

d. Comparison with model calculations

Here, we compare the observational results from the MRI CM21 pyranometers with their simulated counterparts for modeled plane-parallel atmospheres. We have computed the total-band solar radiative properties for modeled air columns between the surface and the TO flight level at 7 km. The column was set in a plane-parallel reference atmosphere (U.S. Standard Atmosphere, 1976; COESA 1976) with the top at 120 km. Band-by-band radiative transfer calculations were carried out using the discrete-ordinate method. The entire solar spectral region was divided into 64 bands. Gaseous
absorption by water vapor, ozone, oxygen, and carbon dioxide were taken into account in terms of the three-term $k$-distribution functions, coefficients for which were determined from the Low-Resolution Transmittance Code–7 (LOWTRAN-7) database (Kneizys et al. 1988). The vertical distribution of water vapor was taken from the humidity profiles measured by radiosondes launched at the CF site for the clear-sky cases, and for the cloudy cases we used those of MWR PROF (microwave radiometer profiles) of the ARM value-added procedures retrieved from the integrated ground-based remote sensors (Turner et al. 1997). The latter humidity profiles were used for the cloudy cases because the MWR PROF provided timely data corresponding to the time intervals denoted by the arrows in Figs. 7b and 8b. In the model calculations, the ground surface was assumed to be a Lambertian reflector with a gray albedo of about 0.1 in the visible region and 0.3 in the near-infrared region. These albedo values were used, consistent with Li et al. (2002), to simulate the broadband surface albedo of about 0.2 measured by the TO albedo runs.

We have also taken into consideration the effects of aerosols by simply assuming a homogeneous aerosol layer, as representative of aerosols in a rural area, of a uniform mixture of water-soluble particles and dustlike particles with an equal optical thickness at wavelength 0.55 $\mu$m. The single scattering properties of aerosols were computed from Mie theory by employing the log-normal size distributions and refractive indexes of dustlike particles and water-soluble particles at relative humidity of 70% from the OPAC (optical properties of aerosols and clouds) model by Hess et al. (1998). For the mixed aerosol model, the concentration of water-soluble particles is about 1000 times larger than that of dustlike particles, and the computed single scattering albedo is almost constant over the wavelength region covered by CM21s, with a mean value of 0.851 in the visible region and 0.846 in the near-IR region. For the clear-sky cases, the aerosol-layer top was set at 3 km above the ground, and we used the aerosol optical thickness measured by the MRI sunphotometer (Shiobara et al. 1996) at the CART CF site. For the overcast sky cases, we added a homogeneous water-cloud layer between the observed heights of the cloud top and bottom. Because there is no current information available about aerosol composition and optical thickness for the cloudy cases, we assumed a similar aerosol layer with a presumed optical thickness of 0.1 between the surface and
the cloud-top height. In the cloud layer, aerosols were assumed to be externally mixed with cloud droplets (interstitial aerosol model).

The mean effective cloud-particle radius was estimated from the cloud-particle size distributions measured with a Forward Scattering Spectrometer Probe (FSSP) installed on the University of North Dakota (UND) Cessna Citation in the ARM Spring 2000 Cloud intensive observation period (IOP) dataset (Mace et al. 2000; Marchand 2001, personal communication, available online at ftp://ftp.pnl.gov/pub/outgoing/roj/ARESE_JLFieldData.tar.gz). The single scattering properties of cloud particles were computed from Mie theory using the FSSP-measured cloud-particle size distributions. The visible optical thickness \( \tau_v \) of the water-cloud layer can be estimated from the MWR-measured liquid water path (LWP) and FSSP-measured cloud-particle effective radius \( r_{\text{eff}} \) through the approximate relationship \( \tau_v = 3 \text{LWP}(2 r_{\text{eff}}) \). However, the LWP measured by MWR from the surface may be affected by drizzle and clouds above and below the cloud layer of interest. Actually, for the 21 March case (Fig. 8), there were overhead clouds above the TO flight levels. So, in this study, we adjusted the visible optical thickness of the modeled cloud layer so that the computed total-band reflectance of the cloudy air columns agreed with the measured reflectance. Thus, estimated cloud optical thickness for the 3 March case was almost coincident with that estimated from the MWR-measured LWP together with the FSSP-derived \( r_{\text{eff}} \). The aerosol and cloud parameters that were used are summarized in Table 1. The computed absorptance for the cloudy air columns may contain uncertainties as great as \( \pm 0.02 \) due to uncertainties in the optical properties of the aerosol model, the vertical profiles of water vapor, and cloud microphysical properties as well as in the value of the surface albedo.

In Table 1, we compare the radiative properties evaluated from the CM21 irradiance data with those computed for the modeled air columns. For the overcast sky cases (3 March and 21 March), we made comparison for each observation time interval divided according to the cloud structure changes as shown in Figs. 7b and 8b. Figure 9 illustrates comparisons between the measured and computed absorptances for the clear-sky and overcast-sky cases. Table 1 and Fig. 9 reveal that the measured and computed radiative properties agree well within the measurement and calculation accuracies both for the clear-sky and overcast-sky cases. This means that the measured solar absorption by the clear and overcast air columns was reasonable, and there was no evidence of the so-called anomalous solar absorption in the total-band solar irradiance data measured by the MRI radiometers. This conclusion is consistent with the results of other studies (e.g., Ackerman et al. 2003; Orlooulos et al. 2003; Li et al. 2002).

Without aerosols, the model computation yields a clear-sky absorptance of 0.101 and 0.114 for the 27 February and 20 March cases, respectively. This means that absorbing aerosols could contribute 16%–19% of the measured absorptances of clear-sky columns. On the other hand, for the overcast-sky cases, the model computation for the cloudy air columns without aerosols gives slightly less absorptance values than the measured ones; the reduced absorptance amounts, on average, to 0.013. This amount is still within the uncertainties involved in the measurements and calculations. Therefore, we could not judge whether absorbing aerosols actually affected the total-band absorptance measured for the overcast sky cases. Spectral and/or visible-band measurements may be helpful in investigating aerosol effects on solar absorption by clouds (Asano et al. 2002).

After submission of the present paper, Valero et al. (2003) reported results obtained from their TSBR data. They found that, although their ARESII observational results agreed with the model predictions within the experimental and model uncertainties, the model calculations still systematically underestimated the cloudy-sky absorptances by different amounts depending on the calculation models.

4. Discussion on the enhanced cloud absorption

In the present study, the measured and calculated solar absorptances agreed well for both the clear and overcast air columns. The result indicates no sign of anomalous solar absorption either for the clear-sky or cloudy-sky cases. However, the averaged absorptance for the cloudy air columns was larger than that for the clear air columns by about 0.07; the magnitude is significant, exceeding the measurement uncertainty. This might indicate appearance of the so-called enhanced solar absorption by clouds. Through theoretical simulations of cloud radiative forcing at the top of the atmosphere and at the surface, Chou et al. (1995) and Li and Moreau (1996) suggested that atmospheric solar absorption is sensitive to many factors, especially cloud height and surface...
conditions. Generally, solar absorption by cloudy atmospheres tends to be more enhanced when cloud height is lower, and vice versa.

Here we have investigated quantitatively the effects of cloud heights and vertical profiles of water vapor and aerosols on cloud enhancement phenomena of solar absorption, using the computational scheme and atmospheric models stated above. Only water clouds were considered in this sensitivity study. Figure 10 shows the sensitivity of atmospheric solar absorption to cloud height and thickness by drawing the vertical absorption profiles for three cloud layers. In the figure, the absorption profiles for different cloud optical thicknesses are compared with those for the clear-sky cases. The same reference water-vapor profile was used in all the cases except in the cloud layers, where water vapor was assumed to be saturated at the cloud temperatures. The solar zenith angle and surface albedo were set to 40° and 0.20. For a geometrically thin, low cloud layer (Fig. 10a), there is strong solar absorption in the cloud layer due to absorption by water vapor as well as by cloud droplets, and the absorption is larger for optically thicker cloud layers because of multiple scattering effects. The atmospheric solar absorption is also intensified just above the cloud layer, where water-vapor absorption of the solar radiation reflected back by the cloud layer is added to absorption of the downward solar radiation. On the other hand, although the water vapor density in the atmosphere below a cloud layer is larger than above the cloud layer, the solar absorption is more strongly reduced below a cloud layer that has a larger optical thickness because there is less transmission of solar radiation through optically thicker clouds. As a result, the column absorptance, integrated over the vertical absorption profiles between the surface and the 7-km level, can be greatly enhanced for those cases with cloud layers that are optically thicker and lower, compared with the corresponding clear-sky case. For high-cloud cases (Fig. 10b), although the general features of the vertical absorption profiles above, within, and below the cloud layer are similar to the low-cloud cases, the resultant column absorptance is generally smaller than that for the corresponding clear-sky case. This is because the magnitude of absorption reduction in the atmosphere below the cloud layer is larger than the magnitude of absorption enhancement above and in the cloud layer. The sensitivity calculations for various cloud-top heights suggest that the column absorptances for cloudy cases with a 1-km-thick cloud layer are almost the same as that for the clear-sky case, when the cloud top is at a height around 4–5 km, depending on cloud optical thickness. For geometrically thick cloud layers (Fig. 10c), a strong solar absorption occurs in the upper cloud layer, whereas the absorption rapidly reduces with penetration deep inside the cloud layer. The degree of enhancement of the column absorptance depends on the cloud-top height and optical thickness of a thick cloud layer. In addition to water vapor, aerosols can affect the solar absorption enhancement in cloudy atmospheres in a similar way (figures not shown here); however, the effects depend strongly not only on aerosol optical properties and vertical profiles, but also on
their mixing states in the cloud layer (Asano et al. 2002).

We investigated possible causes of the total-band absorptance enhancement observed for the ARESE II cloudy cases. We compared detailed simulations for the two nearest days of 20 (clear-sky case) and 21 March (cloudy-sky case), for which the enhancement was about 0.06. In the simulation, we adopted different observed water vapor profiles for the two cases; the used water vapor profiles are shown in Fig. 11. Figure 12 shows the relative contributions of dry-air components plus aerosols, water vapor, and cloud to the visible band (0.30–0.72 μm), near-infrared band (0.72–3 μm), and total-band absorptances of the air column between the surface and the 7-km level. The visible-band absorptance is caused mainly by aerosols and, to a lesser degree, by ozone, and it is very sensitive to the optical properties of the aerosols. The aerosol model described in section 3d can contribute the visible band, near-IR band, and total-band absorptances as much as 0.024, 0.020, and 0.023, respectively, for the case in Fig. 12a. On the other hand, the near-infrared absorptance is mainly caused by water vapor. As shown in Fig. 12b, the total-band absorptance calculated for the water vapor profile for 20 March agreed well with the measured absorptance on the day. When the water vapor profile of 20 March is replaced by that of 21 March, the calculated near-infrared absorptance increases by about 0.05, and this results in an increase of 0.03 in the total-band absorptance (Fig. 12c). Further, when a cloud layer is added between the observed cloud-top and cloud-bottom heights, another increase of 0.03 resulted in the total-band absorptance, caused by increased absorption in the cloud layer and in the atmosphere above the cloud layer (Fig. 12d). The present sensitivity study suggests that about half of the observed absorption enhancement of 0.06 could be caused by the larger water vapor content for the cloudy case, compared with the clear-sky case. Another half could be caused by the increased absorption within and above the rather low cloud layer, for the reason discussed above.

5. Conclusions

As an international collaborative research activity in the JACCS program, we have participated in ARESE II with the MRI radiometers. We installed a pair of broadband pyranometers (Kipp & Zonen CM21) on a Twin Otter and deployed the same type of pyranometers, as well as a pyrheliometer and a sun photometer at the ARM SGP CART central facility. The measured radiation data were corrected for temperature dependence and cosine-law response of the pyranometers. The CM21 pyranometers were calibrated through side-by-side comparisons with the SUNY reference radiometers before and after the research flight series at the Blackwell–Tonkawa Airport. In the calibration, we corrected leveling misalignments of the CM21 pyranometers by the method described in the appendix. The accuracy of solar irradiance measurements by the CM21 pyranometers was estimated to be generally better than 20 W m⁻² during the ARESE II period, and an uncertainty of at worst ±0.03 was estimated for the estimated values of the column absorptances.

By carefully analyzing the spatially collocated, total-band solar irradiances measured simultaneously by the airborne and ground-based CM21 pyranometers, we have evaluated solar radiation budgets of the air column between the surface and the TO flight level at approximately 7 km for clear-sky cases on 27 February and 20 March, and for cloudy-sky cases on 3 and 21 March. On the case average, the clear and cloudy air columns absorbed, respectively, about 13% (absorptance of 0.13)
and 20% (absorptance of 0.20) of the total-band solar radiation incident at the top of the air column. We have carried out simulation calculation of the radiative properties for plane-parallel, homogeneous aerosol-cloud-layer models that are based on the measured water vapor profile, effective cloud-particle radius, and aerosol optical thickness. The computed radiative properties for the modeled clear and cloudy air columns reproduced the measured radiative properties reasonably well. The present results indicate no sign of the so-called anomalous solar absorption either for clear-sky or cloudy-sky cases, and this conclusion is consistent with the results of data analysis from other ARESE II radiometers (e.g., Ackerman et al. 2003; Oreopoulos et al. 2003; Li et al. 2002). Furthermore, we investigated, via a simulation calculation, the possible causes of the enhanced total-band absorptance of about 0.07 that was observed for the cloudy-sky cases. It is suggested that about half of the observed enhancement in the total-band absorptance could be caused by the larger water vapor content for the cloudy cases, compared with the clear-sky cases. The other half could be caused by increased absorption within the cloud layer by multiple scattering effects and in the atmosphere above the rather low cloud layer due to additional absorption of the cloud-reflected solar radiation by water vapor.

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APPENDIX

Calibration and Leveling-Misalignment Correction of the MRI CM21 Pyranometers

Here we briefly describe the procedures for determining the calibration constant and for correcting leveling misalignment of the MRI CM21 pyranometers through side-by-side comparison with the SUNY reference radiometers at the Blackwell–Tonkawa Airport. The measured solar irradiance and output voltage of a pyranometer can be related as follows:

\[ G' = AV_o + B. \]  

(A1)

Here \( G' \) is the global irradiance measured by the pyranometer and \( V_o \) is the output voltage that can be adjusted to a reference temperature to correct the temperature dependence discussed in section 2c(1). The coefficients \( A \) and \( B \) are calibration constants to be determined by comparison with the reference global irradiance. On the other hand, the reference global irradiance \( G \) can be written in the form

\[ G = I \cos \theta_o + D, \]  

(A2)

where \( I \) is the direct irradiance normal to the solar beam, \( \theta_o \) is the solar zenith angle, and \( D \) is the diffuse irradiance due to scattered radiation. For the reference irradiance data by SUNY, \( I \) and \( D \) were measured by an Eppley Model AHF cavity radiometer and an Eppley 8–48 pyranometer, respectively (Michalsky et al. 2002).

In the pre- and postflight calibration campaign at the Blackwell–Tonkawa Airport, the CM21 pyranometers were unfortunately misaligned from the horizontal. By taking account of the cosine-law response and misalignment of the pyranometer, the measured global irradiance \( G' \) can be estimated from the reference irradiance \( G \) in the following way. The CM21-measured \( G' \) can be written as

\[ G' = I \cos(i)\Omega(i) + \int_0^{2\pi} \int_0^{\pi} I_{\text{diffuse}}(\mu', \phi')\Omega(\mu') \mu' \ d\mu' \ d\phi', \]  

(A3)

where \( i \) is the angle between the solar direction \((\mu_o = \cos \theta_o, \phi_o)\) and the normal direction \((\mu_n = \cos \theta_n, \phi_n)\) of the pyranometer detector plane given by

\[ \cos(i) = \cos \theta_o \cos \theta_n + \sin \theta_o \sin \theta_n \cos(\phi_o - \phi_n). \]  

(A4)

In (A3), \( \Omega(i) \) is the azimuth mean cosine-response function discussed in section 2c(3). When the pyranometer exactly follows the cosine-law response, then \( \Omega(i) = 1 \) for all \( i \). In Eq. (A3), \( I_{\text{diffuse}} \) is the diffuse radiancne from the direction \((\mu', \phi')\). We do not have exact information on the angular distribution of the diffuse radiance. Furthermore, the contribution of diffuse radiation to the surface global irradiance is usually small under clear-sky conditions. So, in this study, we assumed that diffuse radiation is isotropic and that diffuse irradiance due to isotropic radiation \( I_{\text{diffuse}} \) is the same as the diffuse irradiance \( D \) measured by the reference pyranometer when set correctly in the horizontal level. We then have

\[ \int_0^{2\pi} \int_0^{\pi} I_{\text{diffuse}}(\mu', \phi')\Omega(\mu') \mu' \ d\mu' \ d\phi' = \pi I_{\text{diffuse}} \int_0^{\pi} \mu \Omega(\mu) \ d\mu = D \Psi \]  

(A5)

with

\[ \Psi = 2 \int_0^{\pi} \mu \Omega(\mu) \ d\mu. \]  

(A6)

where \( \Psi \) stands for the pyranometer cosine response to diffuse irradiance, and its value nearly equals 1.0 for
the MRI CM21 pyranometers. Using Eq. (A4), $G'$ in (A3) can be rewritten in the form,

$$G' = I \cos \theta_{\text{a}} \cos(i) \cos \theta_{\text{a}} \Omega(i) + D \Psi. \quad (A7)$$

Because the SUNY direct irradiance $I \cos \theta_{\text{a}}$ and the diffuse irradiance $D$ were independently measured, we can estimate the CM21-measured global irradiance $G'$ from (A7) if we know the deviation angle $i$, which depends on the misaligned inclination angles $(\theta_{\text{a}}, \phi_{\text{a}})$. Under the assumption that the inclination angles are known, by combining (A1) and (A7), the calibration constants $A$ and $B$ can be determined from the datasets of $G'$ and $V$, measured for various values of the solar angles $(\theta_{\text{a}}, \phi_{\text{a}})$. Actually, we could not a priori know the misaligned inclination angles $(\theta_{\text{a}}, \phi_{\text{a}})$. Therefore, we simultaneously determined the calibration coefficients $A$ and $B$ and the most likely values of $(\theta_{\text{a}}, \phi_{\text{a}})$ in the following way. First, for each sampled solar direction $(\theta_{\text{a}}, \phi_{\text{a}})$, we calculate $G'$ at each point on a $0.1^\circ \times 0.1^\circ$ grid for combinations of $\theta_{\text{a}}$ and $\phi_{\text{a}}$ in the ranges of $0 \leq \theta_{\text{a}} \leq 3.0^\circ$ and $0 \leq \phi_{\text{a}} \leq 360^\circ$. Second, using the combined dataset of $G'$ and $V$, we estimate values of $A$ and $B$ by the least squares method, and calculate the rms error at every grid point of $(\theta_{\text{a}}, \phi_{\text{a}})$. Then, we search for the grid point that has the minimum rms error and adopt it as the optimum, giving the best-fitted calibration constant as well as the most likely values of misalignment angles.

### REFERENCES


