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Assessment of multiple scattering and horizontal inhomogeneity in IR radiative transfer calculations of observed thin cirrus clouds

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[1] Outgoing longwave (LW) radiation (OLR) and infrared heating rate errors due to the neglect of multiple scattering by clouds and horizontal cloud inhomogeneity in infrared radiative transfer parameterizations are assessed with a modified version of the *Fu and Liou* [1992] radiative transfer model and field measurements of optically thin cirrus that were observed during the fall 1997 and spring 2000 intensive observation periods conducted at the Atmospheric Radiation Measurement Southern Great Plains site in Oklahoma. A rigorous method is first introduced for incorporating atmospheric and cloud optical and geometric properties derived from measurements in radiative transfer calculations and for ensuring the consistency of these calculations with observations. Part of that method is the use of optical depth derived from measurements of a Multi Filter Rotating Shadowband Radiometer (MFRSR) at 415 nm to determine the cloud ice water content for the longwave and shortwave radiative transfer calculations. The optical depth is corrected to account for forward scattering by cirrus crystals, which is dominant under the thin cirrus conditions observed. Surface downwelling fluxes from the radiative transfer calculations are compared against observations from the Baseline Surface Radiation Network for consistency, with primary emphasis placed on achieving good agreement between the observed and calculated direct normal components. For all cases considered, there is very good agreement in the solar direct irradiance and reasonably good agreement in the solar diffuse irradiance, but without the forward scattering correction the agreement for both would degrade; the diffuse agreement, in particular, would do so by 12 W m^{-2} (>30%). Very good agreement is achieved in the LW with an absolute mean difference of 0.02 W m^{-2}. For the observed cases considered, neglecting multiple scattering of LW by thin cirrus overestimates OLR by 6–8 W m^{-2} or less (depending on cloud optical depth and particle size) because of exclusion of reflection of upwelling LW at the cloud base and results in heating rate errors of as much as 0.2 K d^{-1}. The effect of horizontally homogeneous clouds is approximated by employing the half hourly mean of the derived optical and geometric properties in the calculation. The impact of the combined effect on OLR and LW heating rates is shown from these calculations to be as high as 30 to 35 W m^{-2}, and heating rate errors are on the order of 0.5 to over 1 K d^{-1}, which are very significant errors. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 1610 Global Change: Atmosphere (0315, 0325); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; *KEYWORDS:* Infrared radiation, cirrus clouds, cloud inhomogeniety, surface radiation measurement, IR multiple scattering, validation of radiative transfer calculation

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1. Introduction

[2] Significant attention has been paid to proper treatment of the interaction of clouds with shortwave (SW) radiation given the important role of SW cloud radiative forcing in the climate and the complexity and uncertainties associated with this interaction. Less attention has been given to the treatment of the interaction of clouds with longwave (LW) radiation. The development of sophisticated parameterizations for LW radiative transfer in clouds, e.g., that include the treatment of multiple scattering, has not been a priority in modeling because except in limited spectral regions absorption by water vapor and hydrometeors is the dominant radiative process. Moreover, the limitation of compu-

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tational resources in models made it impractical to develop such LW radiative parameterizations that would undoubtedly compete for computing time with important processes.

1.1. Impact of Multiple Scattering and Cloud Inhomogeniety on IR Radiative Transfer

[3] The issue of LW scattering in cloudy atmospheres is receiving more attention and a picture is emerging that the impact of scattering on LW radiative transfer may be sufficiently significant not to ignore in climate model radiative transfer parameterizations and retrieval algorithms for space-based measurement systems. Calculations in the thermal infrared (IR), particularly at the top of the atmosphere (TOA), may be measurably different when scattering is considered as compared to when it is not considered. *Chou et al.* [1999], for example, showed that neglect of multiple scattering in their analysis produced flux errors at the TOA of as much as 8 W m^{-2}. *Fu et al.* [1997] compared four radiative transfer parameterizations, which included an absorption approximation, a delta-two-stream approximation, a delta-four-stream approximation, and a delta-two-and-four-stream approximation. The parameterizations were compared to a benchmark model: a delta-128 stream discrete ordinate model. The absorption approximation, which neglects scattering, produced fluxes at the TOA that were in excess of the benchmark model by as much as 8 W m^{-2}. *Li and Fu* [2000] later showed that the delta-four-stream approximation provided superior results than the two-stream absorption approximation because it accounted for scatter but more importantly it was better able to handle anisotropic radiation associated with thin cirrus clouds. An important accomplishment of this work is the development of a method of easily accounting for IR cloud scattering in GCMs.

[4] The accuracy of IR radiative transfer calculations may also be affected by assumptions made with respect to cloud geometry. Radiative transfer models typically assume simplistic cloud geometry, e.g., plane parallel, but real clouds have very complex geometry, which may have significantly different effects on IR transfer than that of simple clouds. *Fu et al.* [2000] examined the impact on OLR of assuming horizontally homogenous cloud properties, which is ubiquitous in general circulation models (GCMs) radiative parameterizations. They compared OLR calculated from the plane-parallel homogeneous cloud assumption with that calculated by the independent column approximation. The former method is the standard parameterization for GCMs where clouds in an entire grid are assumed to have a mean optical depth in the horizontal. The latter method calculates the radiative transfer in each cloud column separately utilizing the plane-parallel model for the calculation, and then determines the grid optical depth from the mean of all the independent column cloud optical depths in the grid. Outgoing LW radiation from the plane-parallel assumption underestimated that calculated from the independent column approximation by as much as 14 W m^{-2}, showing that the consideration of cloud geometry is important in IR transfer calculations.

1.2. Importance of Cloud-IR Radiative Interaction in Climate Simulations

[5] Longwave cloud radiative forcing is a critical factor in maintaining and regulating the present climate, and as a result, accurate representation of this process in climate models is important for enabling these models to realistically simulate the present climate and future natural or human-induced climate modifications. The role of LW cloud radiative forcing in the climate is made important through interactive processes involving cloud radiative heating, humidity, and regional and large-scale dynamics. The sensitivity of general circulation patterns to LW cirrus forcing is well documented in the literature [*Slingo and Slingo*, 1988; *Randall et al.*, 1989; *Sherwood et al.*, 1994; *Lohmann and Roeckner*, 1995]. *Lohmann and Roeckner* [1995], in particular, provide evidence of a radiative-hydrological-dynamical feedback mechanism as a means for cirrus effect on circulation. They compare three GCM equilibrium simulations: a control present climate simulation and two perturbed simulations, with cirrus emissivity fixed at zero and one. The perturbation simulation in which emissivity was set to zero resulted in a cooling of the upper troposphere which weakened meridional circulation, but the most significant effect was on the Walker circulation and Asian summer monsoon. Convective activity in critical regions such as the West Pacific warm pool and Indian subcontinent was significantly weakened, thereby dramatically reducing the diabatic heating. The latter perturbation reverses these dynamical features.

[6] On the basis of the modeling studies described above and of radiative studies [e.g., *Chou et al.*, 1999; *Fu et al.*, 2000; *Joseph*, 2000] it is anticipated that the radiative effects from consideration of IR multiple scattering and cloud geometry are sufficient to impact model simulations.

[7] The objective of this study is to further examine the effects of multiple scattering in cloudy atmospheres and cloud inhomogeneity on IR radiative transfer calculations, but unlike previous studies an attempt is made to associate errors due to these effects with observed cloud fields. Moreover the radiative transfer calculations conducted for this assessment are based on optical and geometric cloud properties derive from passive and active measurements, respectively and are validated to ensure that both the calculated IR and solar fluxes at the surface are consistent with observations. The present study further differs from previous studies in that as part of the model validation it introduces a rigorous method for accounting for the effects of forward scattering by cirrus ice crystals that compromise retrieval of cloud optical depth from passive measurements and model-to-observation comparisons under optically thin cirrus conditions.

[8] The study is organized according to the following. Section 2 describes the radiative transfer model and calculation employed in the study. The optical and geometric characteristics of the cloudy cases selected for the study, and the cloud and aerosol optical depth retrieval method are also presented in section 2. Section 3 discusses the model validation and section 4 presents the results from calculations to evaluate IR multiple scattering and horizontal cloud inhomogeneity.

2. Model and Observations

2.1. Radiative Transfer Model

[9] The radiation calculations are carried out with a modified version of the *Fu and Liou* [1992] model and

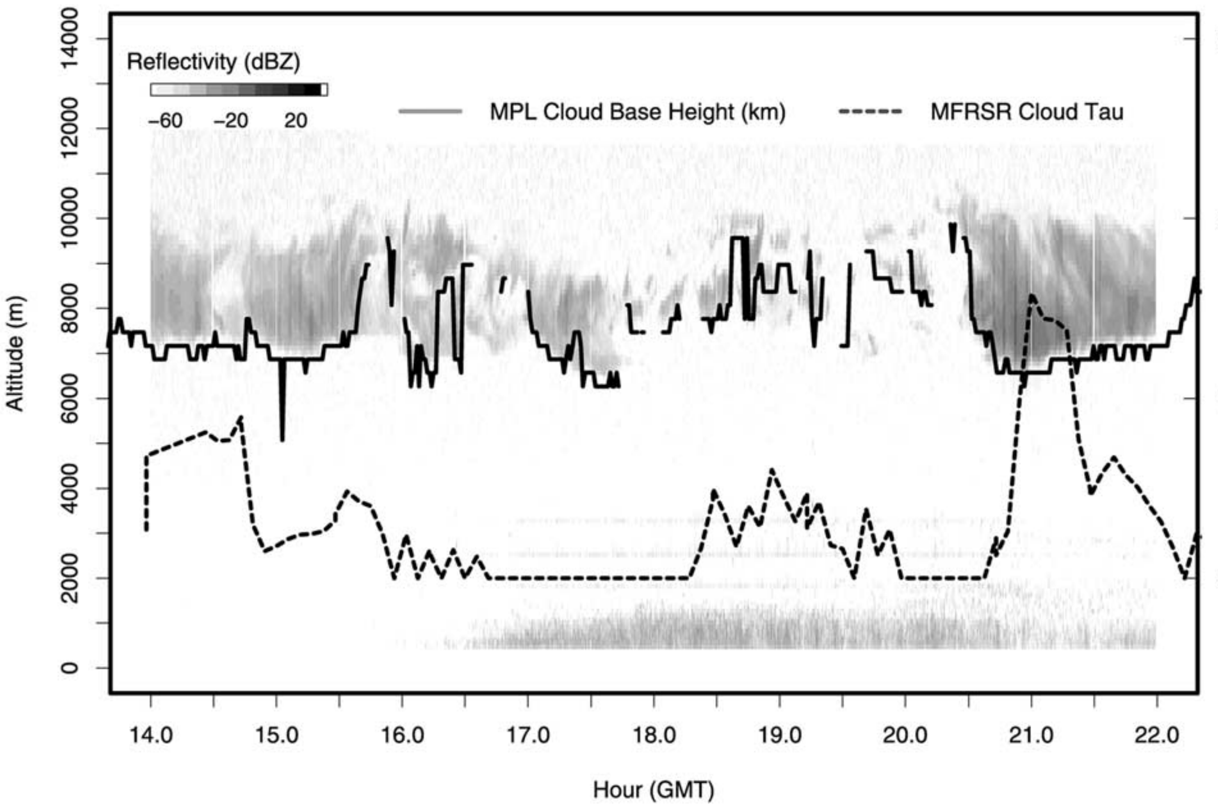

Figure 1. Time series of cloud properties observed on 28 October 1997 at Central Facility of ARM SGP site. Radar reflectivity (dBZ) is from the ARM MMCR; cloud base height (solid line) is from the ARM MPL; and cloud optical depth (dashed line) is derived from MFRSR measurements as described in the text.

are based on observed meteorological and cloud conditions. A complete description of the radiation model is given by *Fu and Liou* [1992], but a brief description follows. The SW and LW regions are divided into 6 and 12 bands respectively. The cirrus LW and SW optical properties are assumed to be hexagonal ice crystals and are parameterized in terms of a generalized effective radius [*Fu*, 1996; *Fu et al.*, 1998]. A delta-four-stream approximation is used for the LW calculation. The SW parameterization in the model is modified to calculate the “true” direct beam flux by replacing the scaled cloud and aerosol optical depth in the delta approximation by optical depth derived from observation.

2.2. Description of Case Study and Model Calculations

[10] Observations made during the fall 1997 and spring 2000 intensive observation periods (IOPs) at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in Oklahoma are use for this study. These observations include simultaneous and collocated measurements of cloud and aerosol properties, surface radiation, meteorological properties, and other atmospheric constituents from a suit of instruments. The cases chosen for this study from these two IOPs are confined to optically thin cirrus events with no underlying clouds. A characteristic case that was observed during a 6 1/2 hour period on 28 October 1997 is illustrated in Figures 1 and 2. The time series of the radar reflectivity from the ARM millimeter cloud radar (MMCR) plotted in Figure 1 shows the presence of high clouds over the ARM Central Facility (CF) from 14:00 to 22:00 GMT; the coverage includes both broken and unbroken periods. Cloud base height derived from the micro pulse lidar (MPL) is also plotted in Figure 1 (solid line). There is very good agreement between the radar and MPL; both show that the base of the cloud varies from 6.5 to 9 km during the period. The cloud optical depth derived from the Multi Filter Rotating Shadowband Radiometer (MFRSR) operated by the Atmospheric Sciences Research Center of the State University of New York at Albany (dashed line in Figure 1) is 1.5 and below, showing that the cloud can be characterized as optically thin. Interpretation of temperature and relative humidity (Figure 2) profiles from two (Figure 2a, 14:30; and Figure 2b, 17:30) of the four daily soundings made at the CF during the IOP suggests that the temperature of the cloud observed during this case study period was 250 K and lower, further suggesting that the cloud mostly consisted of ice crystals. The cloud properties described above are representative of midlatitude thin cirrus [*Heymsfield et al.*, 1990].

[11] Calculations of the radiative transfer (RT) model are conducted at five-minute temporal intervals over each case study period and coincident with the ARM CF. The approach is similar to *Joseph and Wang* [1999]. The

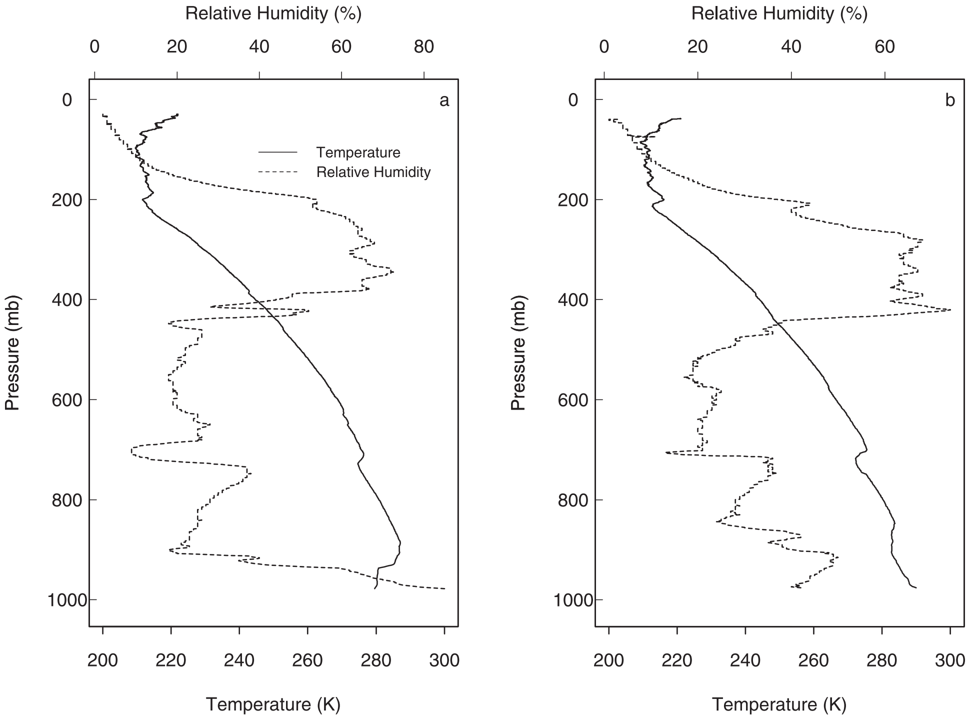

Figure 2. Temperature (K) and relative humidity (%) from sounding taken at ARM SGP Central Facility on 28 October 1997 during the 1997 IOP. Sounding taken at (a) 14:30 GMT and (b) 17:30 GMT.

pressure, temperature and moisture data input for each calculation are interpolated from four daily soundings. Total column water vapor measurements (five-minute averaged) derived from the microwave radiometer are used to constrain the interpolated moisture profiles from the sounding. Local ozone profiles are derived from climatology and scaled to be consistent with total column ozone measurements (TOMs). The insolation for the calculation is determined from the solar constant, adjusted for the day of the year and solar zenith angle, and the surface LW emission and surface temperature are determined from measurements of a down-looking pyrgeometer on a 10-meter tower at the CF. The placement of clouds in specific vertical layers is determined by analysis of lidar base heights, reflectivity from the ARM MMCR and temperature and moisture profiles from the soundings.

2.3. Determination of Cloud and Aerosol Optical Depth

[12] Cloud and aerosol optical depths employed in RT calculations are derived from MFRSR measurements. *Harrison et al.* [1994] describes the measurement technique and *Min and Harrison* [1996] explains the retrieval algorithm. The MFRSR obtains transmittance at six wavelengths (415, 500, 610, 665, 862, and 940 nm). Determination of instantaneous total optical depth is straight forward, and can be obtained from:

$$T_\lambda = \exp(-\tau_{total} m), \qquad (1)$$

where T_λ is the transmittance (instantaneous instrument output for the direct-normal irradiance divided by the extraterrestrial irradiance in the passband), m is the atmospheric air mass and the total optical depth is:

$$\tau_{total} = \tau_{Rayleigh} + \tau_{h2O} + \tau_{O3} + \tau_{aerosol} + \tau_{cloud} \qquad (2)$$

The Rayleigh contribution to the optical depth can be determined and removed from the total optical depth with knowledge of the atmospheric pressure. Ozone extinction in the Chappuis band and that from water vapor can be separated from aerosol and cloud contributions with well-chosen passbands. After the Rayleigh, ozone, and water vapor contributions are removed, what remains is to distinguish between the cloud and aerosol optical depths. Amstronge relationship, given by the following, is used to distinguish between cloud and aerosol:

$$\ln(\tau_\lambda) = \alpha\lambda^{-\beta} \qquad (3)$$

where α is a constant and β is the Amstronge coefficient. The Amstronge coefficient differs for aerosol and clouds across the visible and near-IR region enabling exploitation of this difference for the purpose of distinguishing between aerosol and cloud optical depth. In general, Amstronge coefficient is near zero for clouds, while it is larger than 1.2 for aerosols at the SGP site with a mean of approximately 1.6. The IR cloud optical depth can now be determined with knowledge of the SW cloud optical. The parameterization for SW cloud optical depth in terms of effective particle size (Dge) and cloud ice water path (IWP) from *Fu* [1996] is first used to determine IWP. For this determination an assumption is made for effective particle size, in this case a size of 30 μm is assumed. The derived IWP and assumed Dge are then used in the parameterization from *Fu et al.* [1998] to calculate IR optical depth.

2.4. Accounting for Forward Scattering in Visible Cloud Optical Depth Retrieval

[13] The observations selected for this study are confined to optically thin cirrus conditions because multiple scattering of IR by clouds is dominant under these cloud conditions. From Mie theory, it is known that forward scattering of direct solar irradiance is also dominant under optically thin cirrus condition (tau < 2). Strong forward scattering by cirrus ice crystals enhance transmission into the instrument field of view (FOV), resulting in an "apparent" direct irradiance that is greater than the "true" direct irradiance. The derived cloud optical depth from the MFRSR is therefore smaller than the "true" optical depth. The consequence of this is that the RT model with the derived optical depth will overestimate and underestimate the observed downwelling solar and LW fluxes, respectively at the surface. A method is devised to account for the transmittance due to forward scattering in the determination of the visible optical depth. From *Shiobara and Asano* [1994], the relationship between the apparent and true optical depth is given by:

$$\tau^a = k\tau^t, \tag{4}$$

where the superscripts *a* and *t* signifies true and apparent, respectively. This relationship derives from the relationship for apparent transmission for single scattering approximation:

$$T^a = \exp[-\tau^a] \approx T^d + T^s, \tag{5}$$

where

$$T^d = \exp[-\tau^t]$$

$$T^s = \tau^t \omega P \Delta\Omega \exp[-\tau^t]$$

The direct transmission and transmission due to single scattering are expressed as T^d and T^s, respectively. The remaining terms include, ω, the single scattering albedo, and PΔΩ, the phase function integration over the instrument FOV. On the basis of the geometry of the shadowband of the MFRSR and of the phase function of cirrus at 415 nm, k for the MFRSR is calculated to be 0.52, and the true derived optical depth can be determined from (4). Note that to ensure consistency in model-to-observation comparison of the solar components, the observed flux must also account for the effect of forward scattering. Section 3 below describes a method for achieving this consistency. Error in the observed transmittance measurement from the MFRSR and uncertainty of the phase function correction for forward scattering are the two main sources of uncertainty in determination of true optical depth. The former is known to be better than 1% on the basis of extensive field experience, leaving the major source of uncertainty due to the phase function correction. Sensitivity analysis suggests that the optical depth is uncertain to approximately 5% for the range of zenith angles considered.

3. Model Validation

[14] The calculated surface solar direct and downwelling diffuse, and downwelling IR fluxes are validated against measurements from the Baseline Surface Radiation Network (BSRN) radiometers at the ARM CF to provide a measure of confidence that the calculated OLR and IR cooling rates used to assess IR error due to multiple scattering by clouds, are realistic. Moreover, validation of the solar direct irradiance provides closure for the method of determining the IR optical properties described in section 2.2 since the direct irradiance is directly related to cloud optical depth, e.g., equation (5). Figure 3 includes four scatterplots comparing the calculated solar direct and downwelling diffuse radiation with that from BSRN. The BSRN radiation is provided every one-minute; the five-minute average is determined for the comparison in the figure. Recall that the calculated fluxes are based on observed cloud optical depth that is corrected to account for forward scattering; therefore it is necessary to account for the same effect in the observed fluxes to ensure consistency in the comparison. The FOV of the BSRN was not known but a correction factor, as defined in equation (4), is determined through sensitivity analysis. The transmission into the BSRN pyrheliometer due to forward scattering is removed and applied to the diffuse. A final adjustment is made in all the cases considered to filter broken cloud periods where there is significant variability in the surface radiation and effects of cloud inhomogeneity are dominant, particularly on the diffuse irradiance.

[15] The calculated direct agrees well with the BSRN direct, resulting in a mean absolute difference of 20 W m^{-2} (~ 4% of the mean observed irradiance; Figure 3a). The calculated diffuse also agrees reasonably well with the measured diffuse (Figure 3b). The accuracy of the measured direct and diffuse components, are better than 0.5% and 8%, respectively. As expected the direct irradiance agreement is superior to that of the diffuse, with much more scatter of points in the latter than the former. Assumption in the radiative transfer calculation of a homogeneous cloud layer is a major source of error in the diffuse comparison because in effect the diffuse irradiance is calculated with the same cloud optical properties used to calculate the direct flux. When the optical properties used for the calculation is derived from direct beam measurement of observed cloud fields as in the present case, assuming that the same cloud optical properties for the diffuse and direct calculations are particularly problematic. The measured diffuse component is the integrated hemispheric irradiance over the sensor. Given the inhomogeneity of observed cloud fields, the cloud optical properties that determine this quantity differ from those along the Sun-sensor path, which determines the direct beam measurement. The limitation of the model to account for discrepancy associated with different viewing geometry of inhomogeneous cloud fields contributes to greater scatter of points in the comparison of the calculated and measured diffuse irradiance. A phase difference observed in segments of some comparisons of the times series of the observed and calculated diffuse irradiance (not shown) provides

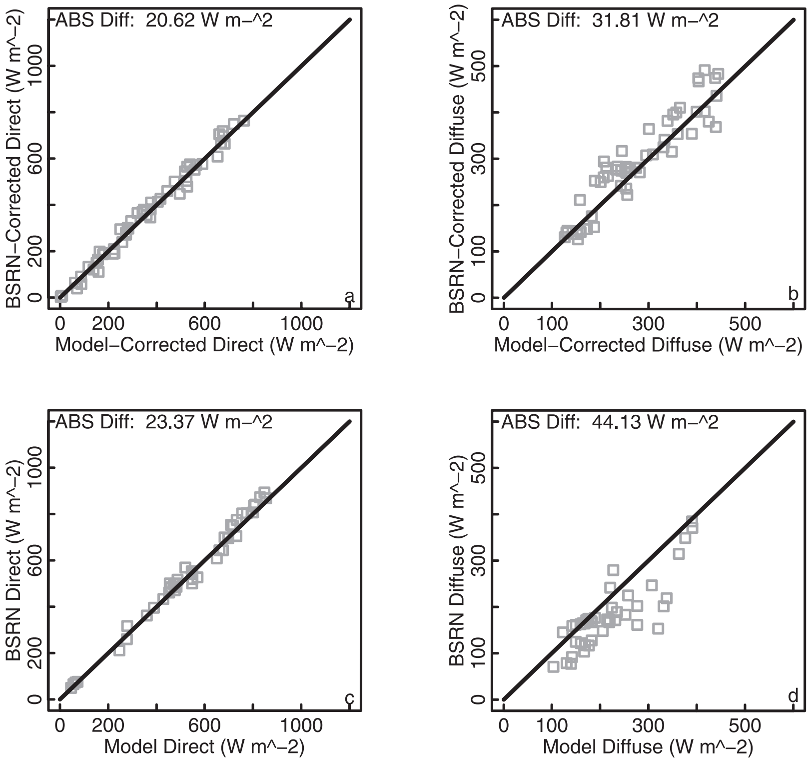

Figure 3. Comparison of measured and calculated surface downwelling broadband solar irradiance for all case study periods: (a) Direct and (b) diffuse. (c and d) Same as Figures 3a and 3b, but before the derived cloud optical depth for the model calculation and the measured flux are corrected to account for transmission into the instrument FOV.

further evidence. The absence of significant scatter of points in the direct comparison reflects the dependency of the direct irradiance on the cloud optical depth along the path of the beam; inhomogeneity of the horizontal cloud optical properties is not a factor in this comparison. Other factors that contribute to errors in the calculated solar components include accuracy of the derived optical depth estimated above to be 5%, assumptions for particle shape and size, and the accuracy of the radiative parameterization. Errors in determination of bulk radiative properties due to the parameterization for single scattering properties is reported by *Fu* [1996] to be 1.2%, 0.3% and 2.9% for reflectance, transmittance and absorptance, respectively. A sensitivity analysis was conducted with respect to effective particle size and the assumption of 30 μm produced optimal agreement between the calculated and observed direct fluxes.

[16] To demonstrate the importance of correcting for the forward scattering, comparisons of the uncorrected direct and diffuse irradiance are shown in Figures 3c and 3d, respectively. Not correcting for forward scattering degrades the direct comparison by 3 W m^{-2} (∼15%) and the diffuse by 12 W m^{-2} (∼40%).

[17] The calculated surface downwelling IR is compared against observation (BSRN) as an additional means of validating the model. Figure 4 shows that the calculated IR agrees well with observation; the mean of the absolute difference is 0.02 W m^{-2}. The uncertainty of observed downwelling IR is generally accepted to be a few W m^{-2}, which is within 0.5%. Uncertainty in the calculated IR is less apparent at the surface as compared to the TOA. A number of factors contribute to that uncertainty including particle shape, the radiative parameterizations and the assumption for effective particle size. An uncertainty of

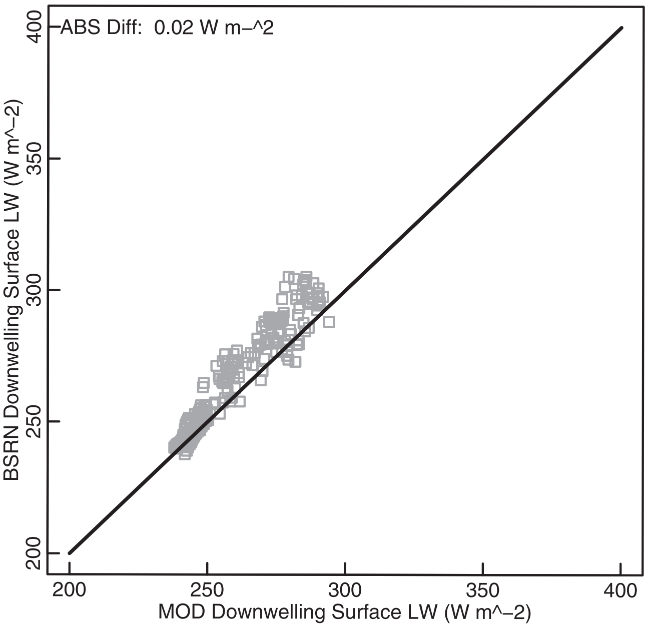

Figure 4. Comparison of measured and calculated surface downwelling broadband IR irradiance (W m^{-2}) for all case study periods.

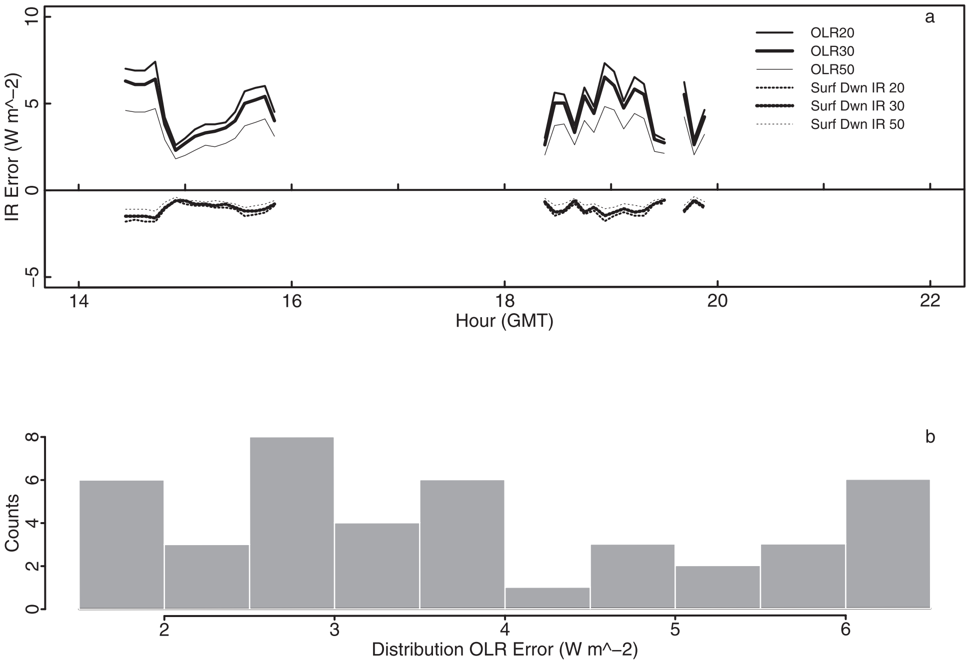

Figure 5. Infrared flux error from neglect of IR scattering by cirrus clouds for (a) 28 October 1997 period and (b) all case study periods (OLR only). For the latter case the error is in terms of mean of the absolute difference.

between 5–10% is estimated on the basis of published results of the parameterization and on the error reported above for the inferred optical depth. The sensitivity to effective particle size is reported in results below.

4. IR Scattering and Horizontal Cloud Inhomogeneity

[18] The impact of IR multiple scattering by cirrus on OLR and IR cooling rates is determined by comparing the following two model calculations over the case study periods: one where the delta-four-stream approximation is applied in the IR calculation (RTS) and one where only IR absorption is considered (RTA). For the latter case the IR optical depth is determined from the absorption coefficient, which depends on effective particle size and ice water content. Additionally the multiple scattering calculation is ignored in the IR transfer parameterization. The OLR (thick solid line) and downwelling surface IR (thick dash line) errors from neglecting scattering by the cloud observed on 28 October 1997 are shown in Figure 5a. The neglect of scattering overestimates the OLR by 6–7 W m^{-2} or less. As expected the error in the surface downwelling IR is much less (<2 W m^{-2}) than that in the OLR. Higher amounts of water vapor in the lower atmosphere mask the effect of high cirrus at the surface. The variability of the error corresponds to the variability of optical depth over the period (Figure 1). The sensitivity of the errors to two assumptions for effective particle size that are different from the default assumption of 30 μm is also shown in Figure 5a. The assumption of a smaller effective particle size (20 μm; medium lines) enhances the cloud optical depth and thus enhances the overestimation at the TOA by as much as 1 W m^{-2}; conversely, the assumption of larger size (50 μm; thin lines) reduces optical depth and thus reduces the over estimation by as much as 2 W m^{-2}. Fifty and 20 μm are reasonable choices to represent the extremes in effective particle size of the cloud observed for this case period. The largest enhancement corresponds to observed optical depth in a range of 0.7–1. As shown in Figure 6 below, this falls within a range where scattering is important and as a result TOA errors are the most sensitive to changes of optical depth. Sensitivity of the error to effective size reduces for cloud

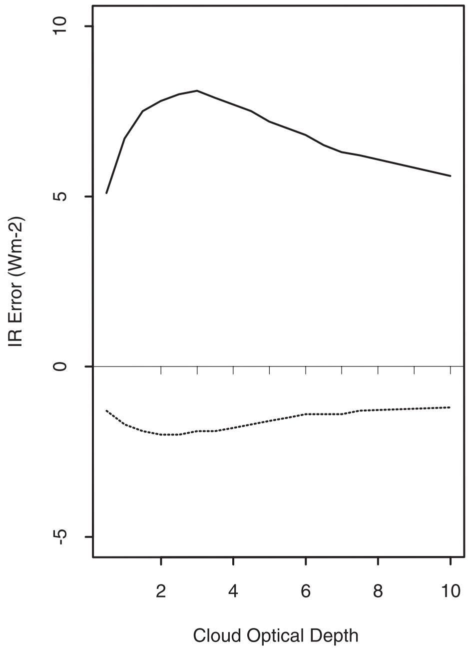

Figure 6. Infrared flux (OLR, solid line; surface downwelling, dashed line) error from neglect of IR scattering by cirrus clouds as a function of artificial cloud optical depths.

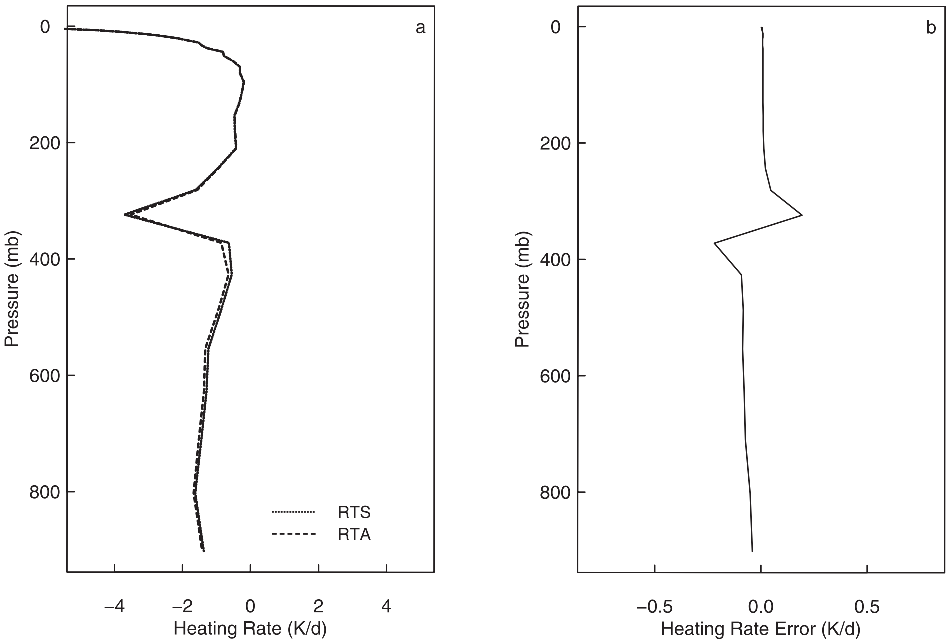

Figure 7. (a) Heating rates (K d^{-1}) from two instantaneous calculations at 14:30 GMT on 28 October 1997: IR cloud absorption and multiple scattering (solid line) and IR cloud absorption only (dashed line). (b) The heating rate error from neglecting scattering.

with larger optical depths. Figure 5b presents a distribution of the OLR error for all cases considered; the results are similar to that in Figure 5a as the errors are confined to approximately 6.5 W m^{-2} or less, and assuming larger or smaller effective particle size alters the error similar to that shown in Figure 5a. The results in Figure 5 of errors in calculated IR due to neglect of multiple scattering are consistent with previous theoretical studies and are due to the exclusion of IR reflection at the cloud base when scattering is neglected. The extent of the error is strongly dependent on optical depth as is evident in Figure 5a, where it varies with the changing optical depth over the period (Figure 1) and assumption of effective particle size. Errors reaching 1 to 2 W m^{-2} larger than the maximum in Figure 5 are possible from cloud optical depths that are slightly larger than those present in the observed sample. Figure 6 shows the result of calculations for a range of artificial values of cloud optical depth above those observed. All other cloud and atmospheric properties are held to the conditions observed on 28 October 1997 for the calculations across the range of optical depth. OLR errors increase from 5 to 8 W m^{-2} for increasing cloud optical depth from 0.5 to 3. Beyond a cloud optical depth of 3 the error decreases asymptotically to a few W m–^{2}. The decrease in the error occurs because for higher values of optical depth cloud absorption becomes a dominant factor.

[19] Impact of the neglect of scattering on calculated heating rates is presented in Figures 7 and 8. Infrared cooling rates and error for a single instantaneous calculation (28 October 1997 at 14:30 GMT) are presented in Figures 7a and 7b, respectively. Above-cloud cooling of −4 K d^{-1} was produced from the cloud observed at 14:30 GMT. The neglect of IR scattering in the calculation results in an above-cloud warming of ~0.2 K d^{-1} and below-cloud cooling of slightly greater than 0.2 K d^{-1}, which is consistent with the results for OLR discussed above. The lack of downwelling IR reflection at the cloud base in the non-scattering calculation results in a warming of the atmosphere above the clouds as compared to calculation where scattering is treated. Figure 8a shows the dependency of the error on cloud optical depth. Plotted are cooling rate errors for a range of observed cloud optical depths. Errors of 0.2 K d^{-1} are associated with the larger optical depths (0.81 and 0.76) and the errors reduce for smaller optical depth. The cloud level corresponding to the cloud optical depth of 0.48 (line with large dashes) is shifted up above the other cases to about 300 mb, thus the heating profile for that case is shifted upward in Figure 8a. The sensitivity of the error to effective particle size is shown in Figure 8b. This sensitivity is for the instantaneous calculation at 14:30 GMT on 28 October 1997. The error increases (~0.1 to 0.3 K d^{-1}) for decreasing effective particle size (50 to 20 μm) since optical depth is inversely proportional to effective particle size.

[20] As discussed in the introduction, climate models assume horizontally homogeneous clouds in their radiative transfer parameterizations but observations like those displayed in Figure 1 show that cloud fields are typically inhomogenous. A crude assessment is conducted to examine the IR and heating rate errors associated with this assumption combined with the effect of neglecting multiple scattering. Horizontally homogeneous clouds are represented in the radiative transfer calculations by the half hourly mean of the derived cloud optical and geometrical properties of the over-passing cloud. The instruments are at a fixed point on the surface; therefore the mean of the derived clouds properties within a specified temporal interval should provide a reasonable approximation of the mean horizontal properties of the over-passing cloud. Non-scattering calculations of OLR and atmospheric heating rates based on half hourly means of the derived cloud and

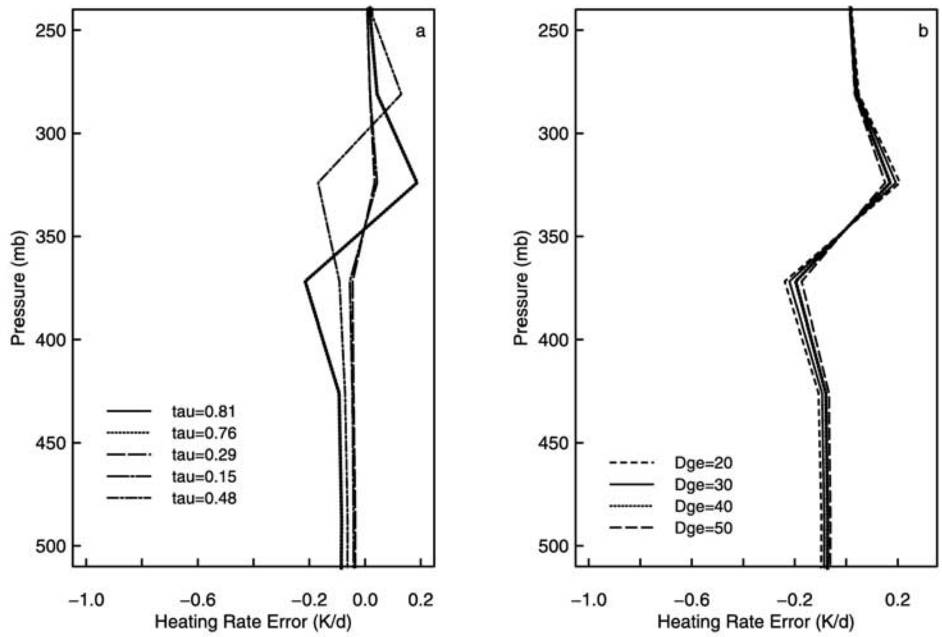

Figure 8. Comparison of heating rate errors among (a) five instantaneous calculations with different observed cloud optical depths and (b) sensitivity of heating rate errors (for 14:30 GMT instantaneous calculation) to four assumptions for effective particle size.

atmospheric properties are conducted as the homogeneous cloud calculation and compared to corresponding results from the RTS calculations described above, which are use as the inhomogeneous cloud calculations. Figure 9 shows the IR flux (OLR and downwelling surface) and heating rate errors for the 28 October 1997 case study period. The sign and extent of the IR error is highly sensitive to the variability of the cloud optical depth in the inhomogeneous calculation from the half hourly mean optical depth in the homogeneous cloud calculation. Errors in the OLR range from a few W m^{-2} to as much as 35 W m^{-2}; a positive (negative) bias results when the inhomogeneous cloud optical depth is greater (less) than the homogeneous optical depth. The effect of neglecting multiple scattering enhances

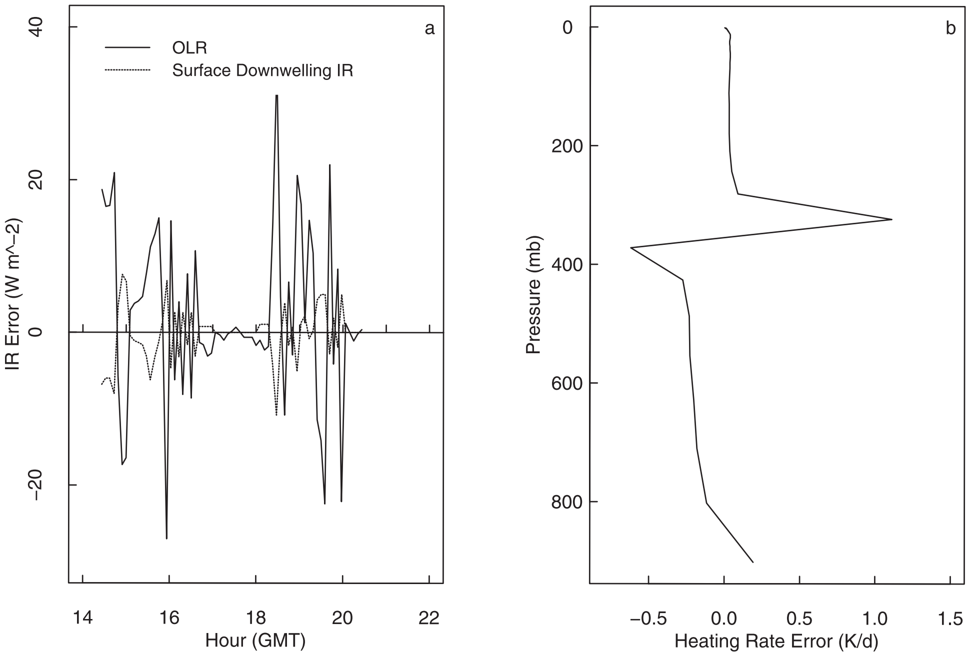

Figure 9. (a) Infrared flux and (b) heating rate error from neglecting horizontal cloud inhomogeneity and IR multiple scattering by cirrus clouds for the 28 October 1997 period. The heating rate error is only for the 14:30 calculation on 28 October 1997.

the positive bias and reduces the negative bias. Downwelling IR errors are less that 10 W m$-^{2}$ and vary in sign opposite that of the OLR error. Heating rate error for 14:30 GMT (Figure 9b) shows above-cloud warming of ~1.5 K d^{-1} and below-cloud cooling of >0.5 K d^{-1}. The sign of the above-and below-cloud heating error reverses for negative OLR bias.

5. Summary and Conclusion

[21] Outgoing LW radiation and IR heating rate errors due to the neglect of multiple scattering by clouds and horizontal cloud inhomogeneity in IR radiative transfer parameterizations are assessed with a modified version of the *Fu and Liou* [1992] radiative transfer model and field measurements of optically thin cirrus that were observed during the fall 1997 and spring 2000 IOPs conducted at the ARM SGP site in Oklahoma. Optically thin cirrus conditions are considered because the effects of IR multiple scattering in clouds are dominant under these conditions. A rigorous method is introduced for integrating, cloud, atmospheric, and radiometric observations with model calculations to ensure that the radiative transfer calculations conducted for the assessment are reliable. Specifically, the calculations are based on observed atmospheric conditions and cloud optical and geometrical properties. In terms of the cloud optical depth, it is derived from measurements of the MFRSR at 415 nm by removing contribution from optically active gases at this wavelength, Rayleigh scattering and aerosols; the aerosol optical depths are used in the calculations. Because the cases considered are confined to optically thin cirrus conditions, the retrieved cloud optical depth is corrected to account for forward scattering by cirrus crystals, which is dominant in the visible region under these conditions. The inferred optical depth after correction is estimated to have an uncertainty of ~5%. Cloud microphysical properties are interpreted from the optical depth, and along with the other observed atmospheric and cloud properties are used for the radiative transfer calculations. The model is then validated to ensure that the surface downwelling solar and IR fluxes are consistent with observations. For all cases considered, there is good agreement in the solar direct irradiance and reasonably good agreement in the solar diffuse irradiance, but without the correction for forward scattering the agreement for both would degrade, the diffuse agreement in particular would do so by 12 W m^{-2} (40%). Very good agreement occurs in the IR with an absolute mean difference of 0.02 W m^{-2}.

[22] The impact on IR heating rates and OLR of neglecting IR multiple scattering is shown to be relatively important. The neglect of scattering overestimates OLR by 6–8 W m^{-2} (~3% of the observed irradiance) or less (depending on cloud optical depth and effective particle size) because of exclusion of reflection of upwelling IR at the cloud base. Calculations based on artificial cloud optical depth show that errors of a few W m^{-2} larger are possible from optical depths 2–3 times larger than that observed. These results are consistent with previous studies. The importance of the impact of neglecting scattering, particularly for climate modeling applications, is demonstrated most in the heating rates. Heating rate errors of as much as 0.2 K d^{-1} are determined, and are shown to be proportional to optical depth and inversely proportional to particle size. Calculations are also conducted to estimate the error due to the combined effect of neglecting multiple scattering by clouds and horizontal inhomogeneity observed in cloud fields in radiative transfer calculations. The effect of horizontally homogeneous clouds is approximated by employing the half hourly mean of the derived optical and geometric properties in the calculation. The impact of the combined effect on OLR and IR heating rates is shown from these calculations to be very significant. Errors in OLR reach as high as 30 to 35 W m^{-2} (~14% of the observed irradiance) and heating rate errors are on the order of 0.5 to over 1 K d^{-1}.

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References

Chou, M. D., K. T. Lee, S. C. Tsay, and Q. Fu, Parameterization for cloud longwave scattering for use in atmospheric models, *J. Clim.*, *12*, 159–169, 1999.

Fu, Q., An accurate parameterization of the solar radiative properties of cirrus clouds for climate models, *J. Clim.*, *9*, 2058–2082, 1996.

Fu, Q., and K. N. Liou, On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres, *J. Atmos. Sci.*, *49*, 2139–2156, 1992.

Fu, Q., K. N. Liou, M. C. Cribb, T. P. Charlock, and A. Grossman, On multiple scattering in thermal infrared radiaitve transfer, *J. Atmos. Sci.*, *54*, 2799–2812, 1997.

Fu, Q., P. Yang, and W. B. Sun, An accurate parameterization of the infrared radiative properties of cirrus clouds for climate models, *J. Clim.*, *11*, 2223–2237, 1998.

Fu, Q., B. Carlin, and G. Mace, Cirrus horizontal inhomogeneity and OLR bias, *Geophys. Res. Lett.*, *27*(20), 3341–3344, 2000.

Harrison, L. C., J. J. Michalsky, and J. Berndt, Automated multi-filter rotation shadowband radiometer: An instrument for optical depth and radiation measurements, *Appl. Opt.*, *33*, 5118–5125, 1994.

Heymsfield, A. J., K. M. Miller, and J. D. Spinhirne, The 27–28 October 1986 FIRE IFO cirrus case study: Cloud microstructure, *Mon. Weather Rev.*, *118*, 2313–2328, 1990.

Joseph, E., Cirrus cloud infrared scattering and absorption in a GCM radiative model, paper presented at 11th Symposium on Global Change Studies, Am. Meteorol. Soc., Long Beach, Calif., 2000.

Joseph, E., and W. C. Wang, An interactive cirrus radiative parameterization for global climate models, *J. Geophys. Res.*, *104*, 9501–9515, 1999.

Li, J., and Q. Fu, Absorption approximation with scattering effect for infrared radiation, *J. Atmos. Sci.*, *57*, 2905–2914, 2000.

Lohmann, U., and E. Roeckner, Influence of cirrus cloud radiative forcing on climate and climate sensitivity in a general circulation model, *J. Geophys. Res.*, *100*, 16,305–16,323, 1995.

Min, Q. L., and L. C. Harrison, Cloud properties derived from surface MFRSR measurements and comparison with GOES results at the ARM SGP Site, *Geophys. Res. Lett.*, *23*(13), 1641–1644, 1996.

Randall, D. A., Harshvardhan, D. A. Dazlich, and T. G. Corsetti, Interactions among radiation, convection and large-scale dynamics in a general circulation model, *J. Atmos. Sci.*, *46*, 1943–1970, 1989.

Sherwood, S. C., V. Ramanathan, T. P. Barnett, M. K. Tyree, and E. Roeckner, Response of an atmospheric general circulation model to radiative forcing of tropical clouds, *J. Geophys. Res.*, *99*, 20,829–20,845, 1994.

Shiobara, M., and S. Asano, Estimation of cirrus optical thickness from sun photometer measurements, *J. Appl. Meteorol.*, *33*, 672–681, 1994.

Slingo, A., and J. M. Slingo, The response of a general circulation to longwave radiative forcing, I, Introduction and initial experiments, *Q. J. R. Meteorol. Soc.*, *114*, 1027–1062, 1988.

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