DEVELOPMENT AND TESTING OF A RADIATION MODEL FOR INTERPRETING ARM DATA (DE-FG03-00ER62931)

Final Report

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A research program devoted to improving the understanding of atmospheric radiation processes has been supported by DOE ARM Grant DE-FG03-00ER62931. This research effort was carried out at the University of Washington from March 16, 2000 to October 31, 2002 with Prof. Qiang Fu as the pincipal investigator. In this report, the major accomplishments from our research efforts are first described in section one. The journal publications that acknowledge DOE ARM Grant DE-FG03-00ER62931 are listed in section two. In section 3, our presentations in the ARM Science Meetings are listed from 2000 to 2002.

1. Major accomplishments

•A high quality data set collected at the ARM SGP CART site is analyzed to identify the water vapor-related anomalous absorption of solar radiation. One of our studies has used the measurements of surface solar irradiances in 3604 clear sky 30-minute segments from January 1994 to September 1998 (Lesins and Fu, 2000 ARM STM). Water vapor profiles from radiosondes and microwave radiometer and aerosol optical depths measured at five wavelengths are input to the Fu-Liou radiation model to provide a comparison with measurements. For the direct beam, the model without considering H_2O continuum absorption in the solar spectrum agrees very well with the measured surface irradiances with a mean excess of only 2.4 W m^{-2} (Fig. 1). The differences in diffuse irradiances between the model and measurements are much larger (14 W m^{-2} after night-time offset correction). Understanding of this difference is still a matter of active research. Nevertheless, we found that the differences between calculated and observed irradiances for both direct and diffuse radiation have little correlation with water vapor, which indicates that the H_2O continuum absorption in the solar wavelengths is small.

A 3D broadband solar radiative transfer scheme has been developed by integrating a Monte-Carlo photon transport algorithm with the Fu-Liou radiation model (Fu et al. 2000a). It was applied to different cloud fields generated by a cloud-resolving model. We found that cloud 3D effects on domain-averaged atmospheric solar absorption is small (less than 4 W m^{-2}). We also found that cloud-related 3D photon transport produces no discernible effects on the absorption due to assumed black carbon aerosol as estimated using the independent column approximation.

Light scattering by spherical particles in an absorbing medium occurs in the earth-atmosphere system, such as cloud particles surrounded by water vapor, and air bubbles in the ocean and sea ice. We have developed analytic solutions for the single-scattering properties of a spherical particle embedded in an absorbing medium (Fu and Sun 2001a). We have derived absorption and scattering efficiencies by using the near filed at the particle surface, which avoids difficulty in obtaining the extinction based on the optical theorem. We found that an absorbing medium can significantly affect the light scattering by a sphere, but have little effect on the particle absorption.

•To improve our understanding of radiative properties of nonspherical ice particles, we have developed a new three-dimensional finite-difference time-domain (FDTD) scheme for light scattering by nonspherical dielectric particles (Sun and Fu 2000). The perfectly matched layer (PML) absorbing boundary condition (ABC) is used to truncate the computational domain. As a result, the present FDTD program requires much less memory and CPU time than those using traditional truncation techniques. Appropriate treatments of the particle snrface and related electric fields are also introduced to improve the FDTD accuracy. For spheres with size parameters as large as 40, we show that the errors in extinction and absorption efficiencies due to the FDTD are less than ~1% and the errors in asymmetry factor are less than 0.1%.

Using the FDTD for nonspherical particles with small size parameters and geometric optics method (GOM) for large size parameters, we have examined a number of commonly used methods for the calculation of the scattering and absorption properties of nonspherical ice crystals at thermal infrared wavelengths. It is found that the anomalous diffraction theory and GOM can underestimate the cirrus emissivity by as large as 30% and 15%, respectively. The Mie theory can either underestimate or overestimate the cirrus emissivity, depending on the definition of equivalent spheres.

•We have examined the outgoing longwave radiation (OLR) bias due to the neglect of cloud horizontal inhomogeneities (Fu et al. 2000b). We found that the OLR bias is most significant for cirrus clouds which are semi-transparent and located in the cold upper troposphere. For two cirrus cases observed at the ARM SGP CART site by cloud radar

(Fig.2), the OLR biases due to the PPH (plane-parallel homogeneous) assumption are ~14 W m^{-2} (Table 1). We have demonstrated that the gamma-weighted radiative transfer scheme can be used to account for the effect of cloud horizontal variability. The effect of cirrus horizontal inhomogeneity on the solar albedo has also been examined (Carlin et al. 2002).

Our research effort has also gone into investigating the effects on domain-averaged solar radiative energy budget due to assumptions about cloud horizontal variability and cloud overlap. We have evaluated the gamma-weighted two-stream approximation using an evolving tropical convective cloud system.

•Most GCMs do not consider the scattering process in the infrared. It is found that the neglect of infrared scattering of clouds would result in an overestimation of the OLR by ~4 W m^{-2} globally. We have developed a fast and accurate parameterization to treat the multiple scattering process in the infrared (Li and Fu 2000). The new parameterization scheme has been incorporated into the CCCMA GCM and is also used in ECMWF NWP model to evaluate the effects of cloud multiple scattering (J.J. Morcrette, personal communication, 2001).

A continuing effort has been made to improve the Fu-Liou radiation model in both accuracy and computational efficiency. This model is used at NASA Langley for processing CERES satellite data on the global scale.

•We have shown that net radiative cooling can be produced by thin cirrus near tropopause above thick convective anvil clouds, which might provide a stratospheric dehydration mechanism that is consistent with available observations (Hartmann et al. 2001a).

The causes of small net cloud radiative forcing in tropical region have been examined by combining data from the ERBE and ISCCP with a radiation model (Hartmann et al. 2001b). A hypothesis is presented that includes feedbacks that drive the net radiation in convective regions toward the net radiation in adjacent non-convective area.

Fu et al. (2002) revisit a model of the feedback processes proposed by Lindzen et al. (2001), in which a reduction in the area of tropical high clouds due to an increase in SST produces a powerful negative feedback associated with upper tropospheric water vapor

and cloud radiative effects. We argue that the high cloud feedback should be small. We also show that the feedbacks related to water vapor and low clouds are significantly overestimated in Lindzen et al. (2001).

2. Journal publications acknowledging DOE ARM grant since 2000

Chin, H.N.S., D.J. Rodriguez, R.T. Cederwall, C.C. Chuang, A.S. Grossman, J.J. Yio, Q. Fu, and M.A. Miller, 2000: A microphysical retrieval scheme for continental low-level stratiform clouds: Impacts of the sub-adiabatic character on microphysical properties and radiation budgets. Mon. Wea. Rev., 128, 2511-2527.

Fu, Q., M.C. Cribb, H.W. Barker, S.K. Krueger, and A. Grossman, 2000a: Cloud geometry effects on atmospheric solar absorption. J. Atmos. Sci., 57, 1156-1168.

Fu, Q., B. Carlin, and G. Mace, 2000b: Cirrus horizontal inhomogeneity and OLR bias. Geophys. Res. Lett., 27, 3341-3344.

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

Sun, W.B., and Q. Fu, 2000: Finite-difference time domain solution of light scattering by dielectric particles with large complex refractive index. Appl. Opt., 39, 5569-5578.

Videen, G., W.B. Sun, Q. Fu, D.R. Secker, R. Greenaway, P.H. Kaye, E. Hirst, and D. Bartley, 2000: Light scattering from deformed droplets and droplets with inclusions: II. Theoretical treatment. Appl. Opt., 39, 5031-5039.

Fu, Q., and W.B. Sun, 2001a: Mie theory for light scattering by a spherical particle in an absorbing medium. Appl. Opt., 40, 1354-1361.

Fu, Q., and W.B. Sun, 2001b: Retrieval of cirrus particle sizes using split-window technique: A sensitivity study. J. Quan. Spectro. Rad. Trsnsfer, 70, 725-736.

Hartmann, D.L., J. Holton, and Q. Fu, 2001a: The radiative tropopause, cirrus, and stratospheric water vapor. Geophys. Res. Lett., 28, 1969-1972.

Hartmann, D.L., L. Moy, and Q. Fu, 2001b: Tropical convection and the energy balance at the top of the atmosphere. J. Climate., 15, 4495-4511.

Sun, W.B., and Q. Fu, 2001: Anomalous diffraction theory for randomly oriented nonspherical particles: A comparison between original and simplified solutions. J. Quan. Spectro. Rad. Trsnsfer, 70, 737-747.

Mitchell, D.L., W. Arnott, C. Schmitt, A. Baran, S. Haveman, and Q. Fu, 2001: Photon tunneling contributions for laboratory grown hexagonal columns. J. Quan. Spectro. Rad. Trsnsfer, 70, 761-776

Fu, Q., M. Baker, D.L. Hartmann, 2002: Tropical cirrus and water vapor: An effective earth infrared iris feedback? Atmos. Chem. Phys. 2, 1-7.

Carlin, B., Q. Fu, U. Lohmann, J.M. Comstock, G.G. Mace, and K. Sassen, 2002: High cloud horizontal inhomogeneity and solar albedo bias. J. Climate., 15, 2321-2339.

Sun, W.B., N.G. Loeb, and Q. Fu, 2002: Finite-difference time-domain solution of light scattering and absorption by particles in an absorbing medium. Appl. Opt., 41, 5728-5743.

Sun, W.B., T. Nousiainen, K. Muinonen, Q. Fu, N.G. Leob, and G. Videen, 2003: Light scattering by Gaussian particles: A solution with finite-difference time domain technique. J. Quan. Spectro. Rad. Trsnsfer, 79-80, 1083-1090.

Sun, W.B., N.G. Loeb, and Q. Fu, 2004: Light scattering by coated sphere immersed in absorbing medium: A comparison between the FDTD and analytic solutions. J. Quan. Spectro. Rad. Trsnsfer, 83, 483-492.

3. ARM Science Team Meeting presentations since 2000

Fu, Q., B. Carlin, and G.G. Mace: Cirrus horizontal inhomogeneity and OLR bias. 13-17 March 2000, San Antonio, Texas.

Fu, Q., and W.B. Sun: Light scattering and absorption by spherical particles in an absorbing medium. 13-17 March 2000, San Antonio, Texas.

Lesins, G., and Q. Fu: Five years of clear sky solar radiation measurements and aerosol forcing at the SGP ARM site. 13-17 March 2000, San Antonio, Texas.

Fu, Q., and W.B. Sun: Retrieval of cirrus particle sizes using a split-window technique: A sensitivity study. 19-23 March 2001, Atlanta, Georgia.

Comstock, J.M., Q. Fu, D.D. Turner, and T.P. Ackerman, 2002: Lidar remote sensing of cirrus clouds at the SGP site: Comparisous of extinction and backscatterer coefficients between Raman and backscatter lidar techniques. 8-12 April 2002, St. Petersburg, Florida.

Boudala, F.S., Q. Fu, and G.A. Isaac, 2002: A GCM parameterization of mean effective ice particle sizes for high latitude cirrus clouds and its comparison with midlatitude parameterizations. 8-12 April 2002, St. Petersburg, Florida.

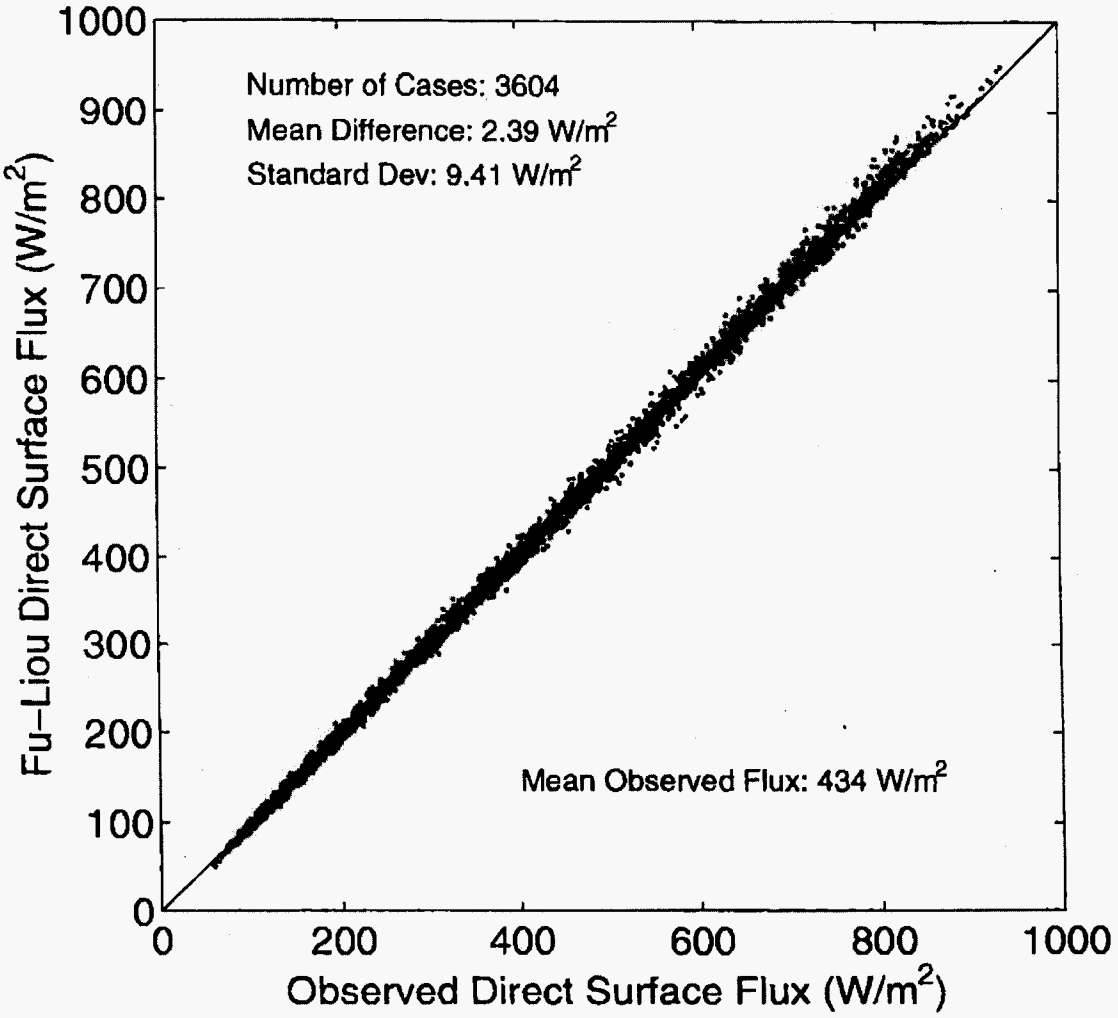

Fig.1. Comparison of solar direct surface flux between the model results and the BSRN pyrheliometer measurements at the ARM SGP central facility under clear sky conditions. Each point represents 30–minute average and the 3604 clear 30–minute segments cover the period from January 1994 to September 1998. We can see an excellent agreement between the model and the observation for the solar direct surface fluxes.

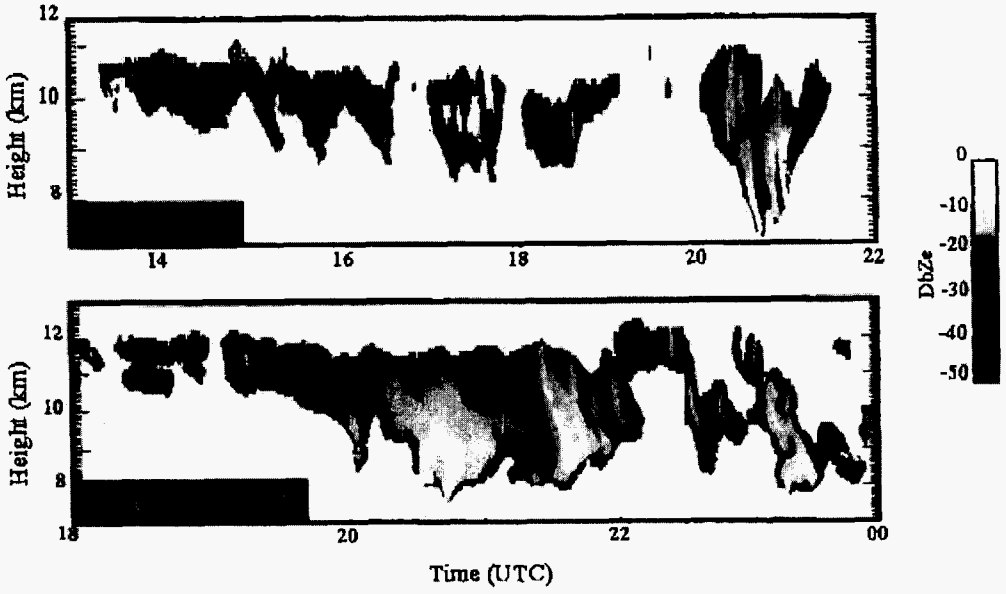

Fig. 2. The height-time cross sections of 35 GHz cloud radar reflectivity for the two cirrus cases of April 18 and September 26, 1997.

Table 1: The mean outgoing longwave radiation ($\overline{OLR}$) for the two cirrus cases as simulated by the independent column approximation (ICA), plane-parallel homogeneous (PPH) model, and the gamma weighted radiative transfer (GWRT) model. The numbers in parentheses are the differences as compared to the ICA results.

	April 18, 1997		September 26, 1997	
	$\bar{\tau}$	σ	$\bar{\tau}$	σ
	0.7046	0.9926	0.8913	0.8828
	$\overline{OLR}$ (W m^{-2})			
ICA	224.7		210.4	
PPH	210.4 (-14.3)		196.7 (-13.7)	
GWRT	224.8 (0.1)		208.5 (-1.9)	