DEVELOPMENT AND TESTING OF A SHORT-WAVE RADIATION MODEL FOR
INTERPRETING ARM DATA

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-FG02-97ER62363. This research effort was carried out at Dalhousie University from January 15, 1997 to March 15, 2000 with Prof. Qiang Fu as the Principal Investigator. The DOE ARM grant was transferred to University of Washington on March 16, 2000, where Prof. Qiang Fu started his new faculty position. This final report requested by DOE is to summarize the entire investigation in Dalhousie University. Our Dalhousie research efforts have concentrated on investigating the solar radiative transfer in clear atmospheres (Fu et al. 1998a; Chylek et al. 1999), studying the effects of 3-D cloud fields on the solar radiative energy budget (Fu et al. 2000; Barker et al. 1999; Barker and Fu 1999), developing a better understanding of radiative properties of nonspherical ice crystals (Fu et al. 1999; Videen et al. 1998; Sun et al. 1999; Sun and Fu 1999; Sun and Fu 2000; Videen et al. 2000), and improving parameterizations of radiation processes for use in GCMs and satellite remote sensing (Fu et al. 1998b; Fu et al. 1997; Li and Fu 2000).

1. Main Results

•A high quality data set collected at the ARM SGP central facility was analyzed to identify the water vapor continuum absorption of solar radiation (Fu et al. 1998a). We focused on the direct solar broadband surface irradiances under cloud-free conditions with large variations of column water vapor amount. The measurements in the April 1994 CAGEX and summer 1996 periods were considered. A radiation model excluding the H₂O continuum in the solar spectrum was compared with observations, which revealed a mean bias of 4.5 W m⁻² (Fig. 1), roughly equivalent to a globally averaged bias of ~2 W m⁻². It is therefore unlikely that the excess absorption suggested by recent studies can be attributed to the H₂O continuum. We also found that the difference between calculated and observed irradiances has a very weak correlation with water vapor. It was suggested that uncertainties associated with aerosols need to be reduced to further narrow the magnitude of the continuum absorption of solar radiation.

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Recently, we have also analyzed the ARM SGP data set to assess radiative forcing caused by atmospheric aerosols under clear sky conditions during a five year period from 1994 to 1998. We first tried to validate the model simulations with observed input data using BSRN surface solar radiation measurements. It is found that the mean difference between the model and measurements in the downward surface direct solar fluxes is only about 2.4 W m^{-2} while the mean difference in the downward surface diffuse fluxes is about 14 W m^{-2} . We have demonstrated that different hypotheses to explain the discrepancy between the model and the measurements results in very different aerosol radiative forcing at the top of the atmosphere. Our study has highlighted the need for a closure experiment which requires an accurate radiation measurement and an observing strategy for the information regarding the aerosol composition and size distributions throughout the atmosphere.

Using water vapor dimer spectral absorption cross-sections derived from quantum mechanical calculations, we investigated the water vapor dimer contribution to the clear sky absorption of solar radiation (Chylek et al. 1998). Here the water vapor dimer concentrations were deduced from experimental measurements of equilibrium constants. We found that water vapor dimer clear sky absorption is nonnegligible for tropical and midlatitude summer types of atmospheres.

- We have developed a 3D broadband solar radiative transfer scheme by integrating a Monte Carlo photon transport algorithm with the Fu-Liou radiation model. It was applied to fields of tropical mesoscale convective clouds and subtropical marine boundary layer clouds; they were generated by a cloud resolving model. The effects of cloud geometry on the radiative energy budget were examined by comparing the full resolution Monte Carlo results with those from the independent column approximation (ICA) which applies the plane-parallel radiation model to each column (Fu et al. 2000).

For the tropical convective cloud system, it was found that cloud geometry effects always enhance atmospheric solar absorption regardless of solar zenith angle. In a large horizontal domain (512 km), differences

in domain-averaged atmospheric absorption between the Monte Carlo and the ICA are less than 4 W m^{-2} . However, for a smaller domain (e.g., 75 km) containing a cluster of deep convective towers, domain-averaged absorption can be enhanced by as much as 20 W m^{-2} in the daytime. For a subtropical marine boundary layer cloud system during the stratus-to-cumulus transition, calculations showed that the ICA works very well for domain-averaged fluxes of the stratocumulus cloud fields even for a very small domain (4.8 km). For the trade cumulus cloud field, the effects of cloud sides and horizontal transport of photons become significant. Calculations have also been made for both cloud systems including black carbon aerosol and a water vapor continuum. It was found that cloud geometry produces no discernible effects on the absorption enhancement due to the black carbon aerosol and water vapor continuum.

Using a 3D broadband solar radiation model along with cloud fields derived from the cloud resolving model, we have also studied the effects of cloud sub-scale variability on the domain-averaged radiative energy budget. It has been shown that the climate models need to account equally well for both cloud horizontal inhomogeneity and cloud overlap (Barker et al. 1999). We have also tested the gamma-weighted two-stream approximation for the treatment of cloud overlap and horizontal inhomogeneity (Barker and Fu 1999).

- A new finite-difference time domain (FDTD) program has been developed to provide an accurate numerical solution for light scattering by nonspherical particles using the perfectly matched layer absorbing boundary condition (Sun et al. 1999; Sun and Fu 2000). As a result, the present FDTD program requires much less computer memory and CPU time than those using traditional absorbing boundary condition. This program can be applied to simulate the light scattering by nonspherical particles with a large range of refractive indices.

Using the FDTD, we have examined the errors in traditional methodologies such as Mie, geometric optics method, and anomalous diffraction theory, for the single-scattering calculations of nonspherical

particles (Fu et al. 1999). It was found that for nonspherical particles, Mie theory using equivalent ice spheres tends to overestimate the absorption efficiency while the anomalous diffraction theory (ADT) and the geometric optics method (GOM) tend to underestimate it. It was also found that the absorption efficiency is not sensitive to the particle shape when the size parameter is large.

We have developed a composite scheme that is valid for nonspherical particles with a wide range of size parameters. The composite method was based on the single-scattering properties of hexagonal particles derived from the GOM for large size parameters and the FDTD for small size parameters. Applying this composite technique, we examined errors in the broadband emissivity of cirrus clouds associated with conventional approaches. It is found that, when the projected area is preserved, Mie results overestimate the emissivity of cirrus clouds while, when the volume is preserved, Mie results underestimate the emissivity. It is also found that the ADT underestimates cirrus cloud emissivity. In some cases, the relative errors can be as large as 30%. The errors in the GOM are also significant and are largely a result of nonspherical particles with size parameters smaller than 30.

Based on improved single-scattering calculations, an accurate parameterization of the infrared radiative properties of cirrus clouds was developed (Fu et al. 1998b), which is well suited for incorporation in climate models to study the climate effects of cirrus clouds.

•A continuing effort has been made to improve the Fu-Liou radiation model in terms of both accuracy and computational efficiency (Fu et al. 1997; Li and Fu 2000). This model is used at NASA Langley for processing CERES satellite data on the global scale.

2. Publications acknowledging DOE ARM Grant DE-FG02-97ER62363:

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

- 2) Li, J., and Q. Fu, 2000: Absorption approximation with scattering effect for infrared radiation. J. Atmos. Sci., 57, 2905-2914.
- 3) 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., (in press).
- 4) 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., (in press).
- 5) 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, 1999: Impacts of the sub-adiabatic character of continental low-level stratiform clouds on microphysical properties and radiation budgets. Mon. Wea. Rev. (accepted).
- 6) Chylek, P., Q. Fu, W. Tso, and D.J.W. Geldart, 1999: Contribution of water vapor dimers to clear sky absorption of solar radiation. Tellus, 51A, 304-313.
- 7) Sun, W.B., and Q. Fu, 1999: Anomalous diffraction theory for arbitrarily oriented hexagonal crystals. J. Quant. Spectro. Rad. Transfer, 63, 727-737.
- 8) Fu, Q., W.B. Sun, and P. Yang, 1999: Modeling of scattering and absorption by nonspherical cirrus ice particles in thermal infrared wavelengths. J. Atmos. Sci., 56, 2937-2947.
- 9) Barker, H.W., and Q. Fu, 1999: Modelling domain-averaged solar fluxes for an evolving tropical cloud system. Atmospheric and Oceanic Optics, 12, 211-217.
- 10) Barker, H.W., G.L. Stephens, Q. Fu, 1999: The sensitivity of domain-averaged solar fluxes to assumptions about cloud geometry. Q. J. Royal Meteorol. Soc., 125, 2127-2152.
- 11) Sun, W.B., Q. Fu, and Z.Z. Chen, 1999: FDTD solution of light scattering by dielectric using PML ABC. Appl. Opt., 38, 3141-3151.
- 12) Videen, G., W.B. Sun and Q. Fu, 1998: Light scattering from irregular tetrahedral aggregates. Opt. Comm., 156,5-9.
- 13) Fu, Q., G. Lesins, J. Higgins, T.P. Charlock, P. Chylek, and J. Michalsky, 1998a: Broadband water vapor absorption of solar radiation tested using ARM data. Geophys. Res. Lett., 25, 1169-1172.

- 14) Fu, Q., P. Yang, and W.B. Sun, 1998b: An accurate parameterization of the infrared radiative properties of cirrus clouds for climate models. *J. Climate*, 11, 2223-2237.
- 15) Fu, Q., K.N. Liou, M.C. Cribb, T.P. Charlock, and A. Grossman, 1997: Multiple scattering parameterization in thermal infrared radiative transfer. *J. Atmos. Sci.*, 54, 2799-2812.

3. DOE ARM Science Team Presentations

13-17 March 2000, San Antonio, Texas

- 1) Carlin, B., Q. Fu, U. Lohmann, G. Mace, J. Barnett, and K. Sassen: Cirrus horizontal inhomogeneity and solar albedo bias.
- 2) Fu, Q., and W.B. Sun: Light scattering and absorption by spherical particles in an absorbing medium.
- 3) Lesins, G. and Q. Fu: Some results and unresolved issues from 5 years of clear-sky solar radiation measurements at the SGP site.
- 4) Fu, Q., and B. Carlin: Cirrus horizontal inhomogeneity and OLR bias.

22-26 March 1999, San Antonio, Texas

- 1) Fu, Q., G. Lesins, and J. Higgins: Aerosol direct radiative forcing: A five year climatology at the ARM SGP CART site.
- 2) Fu, Q., and W.B. Sun: Finite-difference time domain solution for light scattering by nonspherical heterogeneous particles.
- 3) Barker, H.W., E.E. Clothiaux, Z. Li, Q. Fu, T.P. Ackerman, and R.T. Marchand: Overlapping cloud: Intrinsic overlap vs. 'radiative' overlap.
- 4) Barker, H.W., and Q. Fu: Modelling solar fluxes for an evolving tropical cloud system.
- 5) Charlock, T.P., F.G. Rose, T.L. Alberta, Q. Fu, Y. Hu, P. Minnis, J.J. Morcrette, and T. Wong: Application of SGP data to CERES retrievals of shortwave and longwave fluxes.

23-27 March 1998, Tucson, Arizona

- 1) Chin, S., D.J. Rodriguez, R.T. Cederwall, C.C. Chuang, A.S. Grossman, J.J. Yio, Q. Fu, and M.A. Miller: A diagnostic study on

retrieving bulk microphysical properties of low-level stratiform clouds and its implication on climate research.

- 2) Fu, Q., G. Lesins, W.B. Sun, and J. Higgins: Downward surface diffuse solar irradiances in clear atmospheres: Comparison between model and observations.
- 3) Fu, Q., M.C. Cribb, H.W. Barker, and S.K. Krueger: A study of atmospheric absorption of solar radiation using cloud fields derived from a cloud resolving model.
- 4) Fu, Q., G. Lesins, J. Higgins, P. Chylek, T.P. Charlock, and J.J. Michalsky: Water vapor continuum absorption of solar radiation tested using ARM data.

3-7 March 1997, San Antonio, Texas

- 1) Fu, Q., W.B. Sun, and P. Yang: Determination of infrared radiative properties of ice clouds and their parameterizations for climate models.