DOE ASR Final Report on "Radiative Energy Balance in the Tropical Tropopause Layer: An Investigation with ARM Data"

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Project Activities

The overall objective of this project is to use the ARM observational data to improve our understanding of cloud-radiation effects in the tropical tropopause layer (TTL), which is crucial for improving the simulation and prediction of climate and climate change. In last four and half years, we have been concentrating on (i) performing the comparison of the ice cloud properties from the ground-based lidar observations with those from the satellite CALIPSO lidar observations at the ARM TWP sites; (ii) analyzing TTL cirrus and its relation to the tropical planetary waves; (iii) calculating the radiative heating rates using retrieved cloud microphysical properties by combining the ground-based lidar and radar observations at the ARM TWP sites and comparing the results with those using cloud properties retrieved from CloudSat and CALIPSO observations; (iv) comparing macrophysical properties of tropical cirrus clouds from the CALIPSO satellite and from ground-based micropulse and Raman lidar observations; (v) improving the parameterization of optical properties of cirrus clouds with small effective ice particle sizes; and (vi) evaluating the enhanced maximum warming in the tropical upper troposphere simulated by the GCMs. In addition, we have participated the analysis of dust aerosol and radiation observations from the ARM Ancillary Facility (AAF) in a joint China-US Joint Field Experiment in 2008, characterizing the aerosol optical properties over loess plateau of Northwestern China, and investigating the fundamentals of light scattering and radiative transfer which are useful for improving remote sensing retrievals and radiative heating rate calculations. The main results of our research efforts are reported in the 12 referred journal publications that acknowledge the *DOE Grant No. DE-FG02-09ER64769*. Below is a list of these papers followed by the descriptions of the main findings and results.

Main Findings/Results

(i) Statistics of ice cloud macrophysical and optical properties from ground-based lidar observations are compared with those from the satellite CALIPSO lidar observations over a 31-month period. Ground-based lidar observations are taken from the micropulse lidars (MPL) at the three Department of Energy Atmospheric Radiation Measurement (ARM) tropical western pacific (TWP) sites: Manus, Nauru and Darwin. CALIPSO observations show a larger cloud fraction at high altitudes while the ground-based MPLs show a larger cloud fraction at low altitudes. The difference in mean ice cloud top and base heights at the Manus and Nauru sites are all within 0.51 km, although differences are statistically significant. Mean ice cloud geometrical thickness agree to within 0.05 km at the Manus and Nauru sites. Larger differences exist at Darwin due to excessive degradation of the MPL output power during our sampling period. Both sets of observations show thicker clouds during the nighttime which may be real but could also be partially an artifact of the decreased signal-to-noise ratio during the daytime. The number of ice cloud layers per profile are also shown to be consistent after accounting for the difference in spatial resolution. For cloud optical depths, four different retrieval methods are compared, two for each set of observations. All products show that the majority of ice cloud optical depths (~60%) fall below an optical depth of 0.2. For most comparisons all four retrievals agree to within the uncertainty intervals. We find that both CALIPSO retrievals agree best to ground-based optical depths when the lidar ratio in the latter is retrieved instead of set to a fixed value. Also thoroughly compared is the cloud properties for the subset of ice clouds which reside in the tropical tropopause layer (TTL). This work is reported in Thorsen et al. (2011; *J. Geophys. Res*.).

(ii) The spatial and temporal variability of cirrus cloud fraction within the tropical tropopause transition layer (TTL) is investigated based on three years of CALIPSO lidar data, analyzed in conjunction with fields from the ERA-Interim, and temperature profiles from radiosondes launched at ARM Manus site (28S, 1478E). TTL cirrus is found to be mainly confined to the rising branch of the Hadley cell within ~15^o of the equator, with maximum cloud fraction between 14 and 15 km. The time-varying spatial pattern of cloud fraction within this belt does not resemble the pattern of cloud fraction in the layer below, as would be expected if the TTL cirrus were formed by the spreading of the anvils of convective clouds. On the contrary, within the stably stratified layer above ~13 km, cirrus cloud fraction and temperature both appear to be modulated by the planetary-scale vertical velocity field. The time-varying spatial patterns are reminiscent of the vertical-propagating Kelvin wave response to an equatorial heat source, with the coldest, cloudiest air in the TTL centered approximately 30^o of longitude to the east of the strongest heating. Comparison with the ARM data reveals that cirrus occurrence within the TTL and temperature are negatively correlated even at the lowest observed temperatures in radiosonde data at Manus. We find that TTL cirrus is more strongly correlated with temperature than any other variable considered in this study. We interpret this result as indicating that low temperature and high cloud fraction reflect a recent history of planetary-scale ascent. This work is reported in Virts et al. (2010; *J. Atmos. Sci*.).

(iii) One pronounced feature in AR4 GCM-predicted climate change in the 21st century is the much enhanced maximum warming in the tropical upper troposphere near ~ 200 hPa. This feature has important implications to the climate sensitivity because of its impact on water vapor, lapse rate, and cloud feedbacks and to the change of atmospheric circulations. We examined the GCM-predicted maximum warming in the tropical upper troposphere using MSU (microwave sounding unit)-derived deep-layer temperatures in the tropical upper- and lower-middle troposphere for 1979-2010. While the observations generally support GCM results with tropical deep-layer tropospheric warming faster than surface, it is evident that the AR4 GCMs may exaggerate the increase in static stability between tropical middle and upper troposphere during the last three decades. This work is reported in Fu et al. (2011; *Geophys. Res. Lett*.)

(iv) The ARM's Ancillary Facility (AAF/SMART-COMMIT) was deployed to Zhangye (39.082°N, 100.276°E), which is located in a semidesert area of northwest China, during the period of late April to mid June in 2008. We selected 11 cases to retrieve dust aerosol optical depth (AOD), Angstrom exponent, size distribution, single-scattering albedo (SSA) and asymmetry parameter (ASY) from multifilter rotating shadowband radiometer (MFRSR) measurements. These cases are dominated by large particles with Angstrom exponent values ranging from 0.34 to 0.93. The values of AOD at 0.67 μm range from 0.07 to 0.25. The mean SSA value increases with wavelength from 0.76 ± 0.02 at 0.415 μm to 0.86 ± 0.01 at 0.870 μm, while the mean ASY value decreases from 0.74 ± 0.04 to 0.70 ± 0.02. Before estimating dust aerosol direct radiative forcing, a radiative closure experiment was performed to verify that the retrieved aerosol optical properties and other input parameters to the radiative transfer model appropriately represent atmospheric conditions. The daytime-averaged differences between model simulations and ground observations are −8.5, −2.9, and −2.1 W m−2 for the total, diffuse, and direct normal fluxes, respectively. The mean difference in the instantaneous reflected solar fluxes at the top of atmosphere (TOA) between the model and CERES observations is 8.0 W m−2. The solar aerosol direct radiative forcing (ARF), averaged over a 24 h period, at the surface is −22.4 ± 8.9 W m−2, while the TOA ARF is small and has an average value of only 0.52 ± 1.69 W m−2. The daily averaged surface aerosol radiative forcing efficiency at 0.5 μm is −95.1 ± 10.3 W m−2 τ−1. Our results illustrate that the primary role of dust aerosol is to alter the distribution of solar radiation within the climate system rather than to reflect solar energy to space. We assess the satellite aerosol optical depth products from Mutiangle Imaging Spectroradiometer (MISR) and Moderate Resolution Imaging Spectroradiometer (MODIS) observations by comparing them with our ground-based retrievals. Reasonable agreements with the ground-based observations are found for the MISR product and MODIS Deep Blue product. This work is reported in Ge et al. (2010; *J. Geophys. Res.*). A further analysis of the AAF data is reported in Ge et al. (2011; *Geophys. Res. Lett.*).

(v) A parameterization of infrared radiative properties of cirrus clouds developed by Fu et al. (1998) based on in-situ observed ice particle size distributions with the consideration of non-spherical ice particles is widely used in GCM applications. This parameterization, however, is only accurate when the effective ice particle size (D_{ge}) is larger than about 15 μm. For tropical tropopause thin/subvisible cirrus, D_{ge} values are often smaller than 15 μm. In this work, we have extended the parameterization to D_{ge} smaller than 15 μm. Regression error for the small D_{ge} parameterization is similar to that of the parameterization in Fu et al. (1998). This work has filled the gap in the current parameterizations of infrared cirrus radiative properties used in climate studies.

Publications Acknowledging *DOE Grant No. DE-FG02-09ER64769*

(1) Thorsen, T.J., Q. Fu, J. Comstock, C. Sivaraman, M. A. Vaughan, D. M. Winker, and D. D. Turner, 2013: Macrophysical properties of tropical cirrus clouds from the CALIPSO satellite and from ground-based micropulse and Raman lidars. *J. Geophys. Res.*, 118 (16), 9209 - 9220, doi: 10.1002/jgrd.50691.

(2) Thorsen, T.J., Q. Fu, and J. Comstock, 2013: Cloud effects on radiative heating rate profiles over Darwin using ARM and A-train radar/lidar observations. *J. Geophys. Res.*, 118 (11), 5637 - 5654, doi: 10.1002/jgrd.50476.

(3) Lin, L., Q. Fu, H. Zhang, J. Su, Q. Yang, and Z. Sun, 2013: Upward mass fluxes in tropical upper troposphere and lower stratosphere derived from radiative transfer calculations. *J. Quant. Spectrosc. Radiat. Transfer*, 117, 114-122, 10.1016/j.jqsrt.2012.11.016.

(4) Po-Chedley, S., and Q. Fu, 2012: Discrepancies in tropical upper tropospheric warming between atmospheric circulation models and satellites. *Environ. Res. Lett.,* 7, 044018 (8pp), doi: 10.1088/1748-9326/7/4/044018.

(5) Thorsen, T.J., Q. Fu, and J. Comstock, 2011: Comparison of the CALIPSO satellite and ground-based observations of cirrus clouds at the ARM TWP sites. *J. Geophys. Res.*, 116, D21203, doi:10.1029/2011JD015970.

(6) Fu, Q., S. Manabe, and C.M. Johanson, 2011: On the tropical upper tropospheric warming: Models versus observations. Geophys. Res. Lett., 38, L15704, doi:10.1029/2011GL048101.

(7) Ge, J.M., J.P. Huang, J. Su, J.R. Bi, and Q. Fu, 2011: Shortwave radiative closure experiment and direct forcing of dust aerosol over Northwestern China. *Geophys. Res. Lett.*, 38, L24803, doi:10.1029/2011GL049571.

(8) Bi, J.R., J.P. Huang, Q. Fu, X. Wang, J.S. Shi, W. Zhang, Z.W. Huang, B.D. Zhang, 2011: Toward characterization of the aerosol optical properties over loess plateau of Northwestern China. *Quan. Spectro. Rad. Transfer*, 112, 346-360, doi:10.1016/j.jqsrt.2010.09.006.

(9) Ge, J.M., J. Su, Q. Fu, T.P. Ackerman, and J.P. Huang, 2011: Dust aerosol forward scattering effects on ground-based aerosol optical depth retrievals. *Quan. Spectro. Rad. Transfer*, 112, 310-319, doi:10.1016/j.jqsrt.2010.07.006.

(10) Virts, K.S., J.M. Wallace, Q. Fu, and T.P. Ackerman, 2010: TTL cirrus: Formation mechanisms and association with planetary scale waves. *J. Atoms. Sci.*, 67, 3113-3129.

(11) Zhang, H., F. Zhang, Q. Fu, Z.P. Shen, and P. Lu, 2010: Two- and four-stream combination approximations for computation of diffuse actinic fluxes. *J. Atmos. Sci*., 67, 3238-3252.

(12) Ge J.M., J. Su, T.P. Ackerman, Q. Fu, J.P. Huang, and J.S. Shi, 2010: Dust Aerosol Optical Properties Retrieval and Radiative Forcing over Northwestern China during the 2008 China-US Joint Field Experiment. *J. Geophy. Res.,* 115, D00K12, doi:10.1029/2009JD013263.

ARS STM Presentations

Thorsen, T., Q. Fu, J. Comstock: Comparison of the CALIPSO satellite and ground-based observations of cirrus clouds at the ARM TWP sites. *2010 ASR Science Team Meeting,* March 15 to 19, 2010, Bethesda, Maryland.

Thorsen, T., Q. Fu, J. Comstock: Radiative heating rate profiles at the ARM TWP Manus site using cloud properties from a combined remote sensor retrieval. *2011 ASR Science Team Meeting,* March 28 to April 1, 2011, San Antonio, Texas.

Thorsen, T., Q. Fu, J. Comstock: Radiative heating rate profiles over the ARM TWP sites using inputs from multiple ground-based and satellite remote sensors. *2012 ASR Science Team Meeting,* March 12 to March 16, 2012, Arlington, Virginia.

Thorsen, T.J., Q. Fu, J. Comstock, C. Sivaraman, M. A. Vaughan, D. M. Winker, and D. D. Turner: Macrophysical properties of tropical cirrus clouds from the CALIPSO satellite and from ground-based micropulse and Raman lidars. *2013 ASR Science Team Meeting,* March 17 to 21, 2013, Potomac, Maryland.