Final Progress Report

DE-FG02-05ER64069

1. PI: Z. Wang

2. Title of Research Grant: Using Radar, Lidar, and Radiometer measurements to Classify Cloud Type and Study Middle-Level Cloud Properties

3. Scientific Goal(s):

The project is mainly focused on the characterization of cloud macrophysical and microphysical properties, especially for mixed-phased clouds and middle level ice clouds by combining radar, lidar, and radiometer measurements available from the ACRF sites. First, an advanced mixed-phase cloud retrieval algorithm will be developed to cover all mixed-phase clouds observed at the ACRF NSA site. The algorithm will be applied to the ACRF NSA observations to generate a long-term arctic mixed-phase cloud product for model validations and arctic mixed-phase cloud processes studies. To improve the representation of arctic mixed-phase clouds in GCMs, an advanced understanding of mixed-phase cloud processes is needed. By combining retrieved mixed-phase cloud microphysical properties with *in situ* data and large-scale meteorological data, the project aim to better understand the generations of ice crystals in supercooled water clouds, the maintenance mechanisms of the arctic mixed-phase clouds, and their connections with large-scale dynamics. The project will try to develop a new retrieval algorithm to study more complex mixed-phase clouds observed at the ACRF SGP site.

Compared with optically thin ice clouds, optically thick middle level ice clouds are less studied because of limited available tools. The project will develop a new two-wavelength radar technique for optically thick ice cloud study at SGP site by combining the MMCR with the W-band radar measurements. With this new algorithm, the SGP site will have a better capability to study all ice clouds.

Another area of the proposal is to generate long-term cloud type classification product for the multiple ACRF sites. The cloud type classification product will not only facilitates the generation of the integrated cloud product by applying different retrieval algorithms to different types of clouds operationally, but will also support other research to better understand cloud properties and to validate model simulations. The ultimate goal is to improve our cloud classification algorithm into a VAP.

4. Accomplishments:

- An improved microwave radiometer liquid water path (LWP) retrieval algorithm was developed to provide more accurate LWP, especially for low LWP observed at the NSA site.

- An advanced multi-sensor mixed-phase cloud retrieval algorithm was developed to cover single-layer stratiform mixed-phase clouds in all LWP range.
- A dual-wavelength radar retrieval algorithm for optically thick ice clouds was developed for WACR and MMCR measurements.
- Our cloud classification algorithm was transferred into a VAP.
- Cloud microphysical and macrophysical properties during the M-PACE were provided to the Cloud Modeling and Parameterization group to support the model validation efforts.
- ECMWF and climate model simulations were evaluated with multi-year observations at the NSA site to better understand model weakness.
- The impact of large-scale dynamics on cloud properties at the NSA site was studied.

5. Progress Description:

a) An improved MWR LWP retrieval algorithm

Traditional two-channel microwave radiometers (MWR) are widely used to measure cloud liquid water path (LWP); however, relatively large uncertainties occur in the retrieved LWP, especially for low LWP clouds. By reformulating the statistical retrieval method with clear sky measurements as a reference, a simple method is presented to significantly reduce LWP retrieval uncertainties due to uncertainties in MWR calibration, absorption coefficients of atmospheric gases, and variability in the vertical profiles of temperature and pressure (Wang 2007). Comparison of retrieved LWPs (Shown in Fig. 1) from a multiple-sensor algorithm and algorithms mainly based on MWR measurements, and the statistics of a clear sky MWR LWP based on the ACRF observations at the NSA site illustrate the improvement obtained with this algorithm. In this study, we also demonstrated the importance of using the correct water cloud temperature and temperature-dependent water absorption coefficient for the MWR LWP retrieval over cold regions. The improved approach can be easily implemented with MWR, ceilometer and surface meteorological measurements. Using this algorithm, accurate LWP at the NSA site can be provided using data collected from 1998 onwards – an important application which takes advantage of the long-term observations collected at the NSA site

b) An advanced multiple-sensor mixed-phase cloud retrieval algorithm

We have developed an advanced retrieval algorithm for stratiform mixed-phase clouds (all LWP range) based on MPL, MMCR, MWR and radiosonde measurements (Wang et al. 2007). This algorithm is capable of providing profiles of ice water content (*IWC*) and ice general effective radius (D_{ge}) for characterization of the ice phase and *LWP* and water cloud effective radius (r_{eff}) profile for characterization of the water phase in the mixed-phase clouds. With these four cloud properties we can quantify the radiative impacts of mixed phase clouds and investigate many of the microphysical processes that are important in arctic mixed-phase clouds. A lidar-radar algorithm (Wang and Sassen 2002), which has been validated through algorithm inter-comparison (Comstock et al 2007) and using in situ data (Heymisfield et al. 2008), has been applied to MPL (below the base of the mixed-phase cloud layer) and MMCR data to provide profiles of IWC and D_{ge}. The MWR- and MPL-retrieved cloud extinction coefficients are then used to derive LWP and r_{eff} for the liquid phase. An example of retrievals is presented in Fig. 2 based on measurements during the M-PACE. This algorithm was validated using in situ measurements from the M-PACE experiments. Retrieved r_{eff} profiles agree with the in situ data to better than 10%. One source of uncertainty affecting the retrieved r_{eff} values is the treatment of multiple scattering. We are currently working to refine the correction of multiple scattering to improve the accuracy of the retrieved r_{eff} profile. A journal paper is under preparation.

c) Cloud classification VAP development

We have made significant progress in improving the cloud classification algorithm. The algorithm was coded in IDL, and was delivered to Jennifer Comstock (the ARM cloud working group translator) and Chaomei Lo at the PNNL. It was implemented as a VAP for the SGP observations (Lo et al. 2007).

d) Optically thick ice cloud retrieval with Dual-wavelength radar measurements

A dual-wavelength radar algorithm is developed to retrieve optically thick ice cloud microphysical properties based on MMCR (35 GHz) and WACR (95 GHz) observations at the SGP site (Miao and Wang 2009). The algorithm utilizes particle size information embedded in the measurements due to strong dependence of particle backscattering on particle size as wavelength and stronger Mie scattering effect at 95 GHz than at 35 GHz (Wang et al. 2005). The algorithm is able to retrieve ice crystal generalized effective size (D_{ge}) and ice water content (IWC) profiles for optically thick ice clouds, which are very challenging for single-wavelength radar or combined lidar-radar approaches. Retrieval examples with this algorithm are presented in Fig. 3.

e) Supporting the Cloud Modeling and Parameterization Group’s model validation efforts

The M-PACE dataset provides a unique opportunity for evaluating the capability of numerical models to reproduce the characteristics of mixed-phase clouds in the Arctic. The M-PACE dataset has been separated into two periods: (A) consisting of multiple layer cases and (B) consisting of single layer cases to examine the ability of models to simulate mixed-phase clouds under different conditions. In addition to providing LWP for both periods and mixed-phase cloud microphysical properties for period B (Klein et al. 2009; Morrison et al. 2009), at the request of the modelers we developed a new approach to provide multi-layer mixed-phase cloud vertical structure for the period A observations. Without this additional product, model and observation comparisons for period A would have been very limited (Luo et al. 2008). Currently, we are working to generate month-long multi-sensor retrievals during the ISDAC to support ongoing model intercomparison studies.

f) Long-term data analyses and model evaluation

The multi-sensor based mixed-phase retrieval algorithms have been implemented for long-term ACRF observations at the NSA site and generated six-years of mixed-phase cloud microphysical properties (1999-2004). Figure 4 shows that the seasonal variation in cloud effective radius appears to be strongly correlated with the near-surface aerosol extinction coefficient. The ice generation in arctic mixed-phase clouds also has significant seasonal variation, which could be attributed to seasonal arctic aerosol variation. But further detailed study is needed to better link aerosol properties (type and size) with ice generation in mixed-phase clouds. The long-term ACRF observations at the NSA site were also used to understand how large-scale dynamics and boundary layer properties affected boundary layer cloud properties observed at the NSA site (Wang et al. 2008) Arctic boundary layer clouds can form under warm moisture air or cold dry air advections. There are noticeable differences in cloud top height and LWP for clouds formed during warm vs. cold advections. The seasonal cycle in the occurrence of large-scale subsidence and upward motions (based the NCEP reanalysis) over the NSA site, which effects cloud occurrence and LWP (especially in summer), can be clearly seen in Fig. 5. However, the ECMWF simulations show a greater sensitivity to subsidence and upward motions than the observations. The data also show that large-scale dynamics also have a noticeable impact on liquid-ice mass partition in mixed-phase clouds around the NSA site.

Understanding the weaknesses of current models is important for improving model simulations of Arctic clouds. Zhao and Wang (2010) evaluated the ECMWF model-simulated clouds and boundary layer (BL) properties based on ACRF observations at the North Slope of Alaska (NSA) site during 1999-2007. The ECMWF model-simulated near surface humidity had seasonal dependent biases as large as 20%. The ECMWF model had difficulty to represent BL temperature inversion height and strength during the transition seasons. Although the ECMWF model captured the seasonal variation of surface heat fluxes, it had sensible heat flux biases over 20 W/m^2 in most of cold months. The ECMWF model captured the general seasonal variations of low-level cloud fraction (LCF) and liquid water path (LWP). However, the ECMWF model overestimated LCF by 20% or more and underestimated LWP over 50% in the cold season. On average, the ECMWF model underestimated LWP by ~30 gm^{-2}, but correctly predicted ice water path for BL clouds. For BL mixed-phase clouds, the model predicted water-ice mass partition was significantly lower than the observations, largely due to the temperature dependence of water-ice mass partition used in the model. The ECMWF model captured the general response of cloud fraction and LWP on large-scale vertical motion changes, but over-predicted the magnitude of the difference, especially for LWP. As illustrated in Fig. 6, the two major cloud and BL improvements of the ECMWF model after 2003 only resulted in minor improvements in BL cloud simulations in summer. These results indicate that significant improvements in cold season BL and mixed-phase cloud processes in the model are needed.

Current GCMs not only fail to reproduce the annual cycle of cloud amount, significantly under or over estimate LWP, but also that there are large differences in the predicted properties among different models (Miao and Wang 2008). Figure 7 shows the monthly mean values of surface longwave cloud forcing as a function of LWP for ARM observations and three model simulations around the NSA site. The clear differences among models and between model simulations and observation suggest that the representation of arctic clouds in GCMs predicts unrealistic cloud-radiation feedbacks over the Arctic region.

6. Figure Description:

Figure 1. The frequency distributions of retrieved clear-sky LWP values based on MWR observations at the ACRF NSA site during January 1999 and December 2004. Note that the solid line represents the new MWR retrievals discussed here and the dashed line represents ACRF archived retrievals. The narrow distribution of clear-sky LWP indicates that the refined method has a better accuracy.

Figure 2. A retrieval example of an advanced mixed-phase cloud algorithm based on measurements of 10 October 2004 during the M-PACE. From top to bottom are MMCR radar reflectivity, Cloud extinction coefficients retrieved from MPL measurements, and retrieved water cloud effective radius profiles, LWP, IWC profiles, and ice particle D_{ge} profiles. The red line in the LWP plot is retrieved from MWR measurements with the new method we developed and black line is adiabatic values calculated based water cloud base and top. Meanwhile, LWP values based on in situ measurements are presented with triangle symbols.

Figure 3. Retrieval examples of optically thick ice clouds with dual-wavelength radar measurements at the SGP site. From top to bottom are WACR reflectivity factor (Z_e), MMCR Z_e, Dual-wavelength Z_e ratio (DWR), and retrieved Dge and IWC profiles. Different vertical columns represent for different days.

Figure 4. The annual cycle of near surface aerosol extinction coefficient (top) and water cloud effective radius observed at the NSA site from 1999 to 2004. The near surface aerosol extinction coefficients are from NOAA aerosol measurements at the Barrow site. The water cloud effective radius is retrieved from ACRF multiple sensor measurements at the NSA site.

Figure 5. The annual cycle of subsidence and upward conditions and the annual cycle of cloud LWP formed under subsidence and upward conditions separately for observations and ECMWF forecasts at the NSA site during 1999 to 2003. The subsidence and upward conditions are derived based the NCEP reanalysis close to the NSA site.

Figure 6. The ECMWF model performance in predicting low-level cloud fraction (a and b) and liquid water path (c and d) in terms of monthly mean actual difference (model-observation) and relative error (|(model-observation)/observation|) for ECMWF cycles before 2003 (B2003), 29r1, and 31r1.

Figure 7. The dependencies of monthly mean surface longwave cloud radiative forcing on LWP according to ARM observations (1998 to 2008) and three GCM simulations (1990-2010).

7. Refereed Publications

Comstock, J. M., et al. *2007:* An Intercomparison of Microphysical Retrieval Algorithms for Upper Tropospheric Ice Clouds, *Bull. Amer. Meteor. Soc.,* DOI:10.1175/BAMS-88-2-191..

Heymsfield, A. J., et al., 2008: Testing and Evaluation of Ice Water Content Retrieval Methods using Radar and Ancillary Measurements. *J. Appl. Meteor.*, **47**,153-163.

Klein, S. A. et al. 2009: Intercomparison of model simulations of mixed phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment, Part I: Single layer cloud, *Q. J. Roy. Meteor. Soc.*, DOI: 10.1002/qj.416.

Luo, Y., K. Xu, H. Morrison, G. M. McFarquhar, Z. Wang, and G. Zhang, 2008: Multi-layer arctic mixed-phase clouds simulated by a cloud-resolving model: Comparison with ARM observations and sensitivity experiments, *J Geophys Res*, **113**, D12208, doi:10.1029/2007JD009563.

Morrison, H., et al. 2009: Intercomparison of model simulations of mixed phase clouds observed during the ARM Mixed-Phase Arctic Cloud Experiment, Part II: Multi layered cloud, *Q. J. Roy. Meteor. Soc.* , DOI: 10.1002/qj.415.

Turner, D. D., *et al.*, 2007: Thin Liquid Water Clouds: Their Importance and Our Challenge, *Bull. Amer. Meteor. Soc.,* DOI:10.1175/BAMS-88-2-177.

Wang, Z.**,** G. M. Heymsfield, L. Li, and, A. J. Heymsfield, 2005: Retrieve optically thick ice cloud microphysical properties by using airborne dual-wavelength radar measurements. *J. Geophys. Res.*, **110**, D19201, doi:10.1029/2005JD005969.

Wang, Z., 2007: A refined two-channel microwave radiometer liquid water path retrieval for cold regions by using multiple-sensor measurements, *IEEE Geoscience & remote sensing letters,* **4**, 591-595.

Zhao, M. and Z. Wang, 2010: Comparison of Arctic clouds between ECMWF simulations and ACRF long-term Observations at the Barrow Site, *J. Geophys. Res.*, (submitted).

8. Extended Abstracts

Wang, Z., Q. Miao, and M. Zhao 2007: A Long-term Cloud Microphysical Properties Dataset for Arctic Cloud Study Based on ACRF NSA Site Observations. *Proceedings of the Seventeenth ARM Science Team Meeting*, March 26 to 30, 2007, Monterey, California.

Comstock, J., R. Lin, D. Starr, Z. Wang, 2007: Understanding Ice Supersaturation and Particle Growth in Cirrus Clouds Using ARM Measurements and an Explicit Cloud Model. *Proceedings of the Seventeenth ARM Science Team Meeting*, March 26 to 30, 2007, Monterey, California.

Zhao, M., and Z. Wang, 2007: Comparison of Cloud Fraction and Liquid Water Path Between ECMWF Simulations and ARM Long-term Observations at the NSA Site. *Proceedings of the Seventeenth ARM Science Team Meeting*, March 26 to 30, 2007, Monterey, California.

Lo, C., J. Comstock, Z. Wang, 2007: Cloud Type and Cloud Phase Classification Using Ground-Based Active and Passive Remote Sensors. *Proceedings of the Seventeenth ARM Science Team Meeting*, March 26 to 30, 2007, Monterey, California.

Wang, Z., M. Zhao, and M. Deng, 2008: Understanding the Seasonal and Interannual Variations of Boundary-layer Mixed-phase Cloud Properties Observed at the ARCF NSA site. *Proceedings of the Eighteenth ARM Science Team Meeting*, March 10 to 14, 2008, Norfolk, Virginia.

Miao, Q. and Z. Wang 2008: Comparison on Cloud and radiation properties at Barrow between ARCF/NSA measurements and GCM outputs. *Proceedings of the Eighteenth ARM Science Team Meeting*, March 10 to 14, 2008, Norfolk, Virginia.

Naud C., A. Del Genio, M. Haeffelin, Y. Morille, V. Noel, D. Turner, Z. Wang, J. Comstock, and C. Lo, 2008: Cloud Thermodynamic Phase Distribution in Midlatitude Optically Thin Clouds. *Proceedings of the Eighteenth ARM Science Team Meeting*, March 10 to 14, 2008, Norfolk, Virginia.

Comstock, J., N. Beagley, W. Wang, R. Maechand, and Z. Wang, 2008: Analysis of Upper Tropospheric Cloud Properties and Water Vapor Variability in Relation to the Large-scale Atmospheric State. *Proceedings of the Eighteenth ARM Science Team Meeting*, March 10 to 14, 2008, Norfolk, Virginia.

Miao, Q. and Z. Wang, 2009: Retrieving optically thick ice cloud microphysical properties by ground-based dual-wavelength radar measurements at ARM/SGP, in *Proceedings of the Nineteenth ARM Science Team Meeting*, March 30 to April 4, 2009, Louisville, Kentucky.

Sivaraman, C., J. Comstock, C. Flynn, Z. Wang, and K. Johnson, 2010: Routine cloud boundary algorithm development for ARM micropulse lidar. The First Atmospheric System Research (ASR) Science Team Meeting, ASR-CONF-2010, March 15-19, 2010, Bethesda, Maryland.

Wang, Z. and M. Zhao, 2010: Insights on Water-Ice Partition in Stratiform Mixed-phase Clouds based on Long-term ARCF Observations. The First Atmospheric System Research (ASR) Science Team Meeting, ASR-CONF-2010, March 15-19, 2010, Bethesda, Maryland.

9. Updated Status:

None

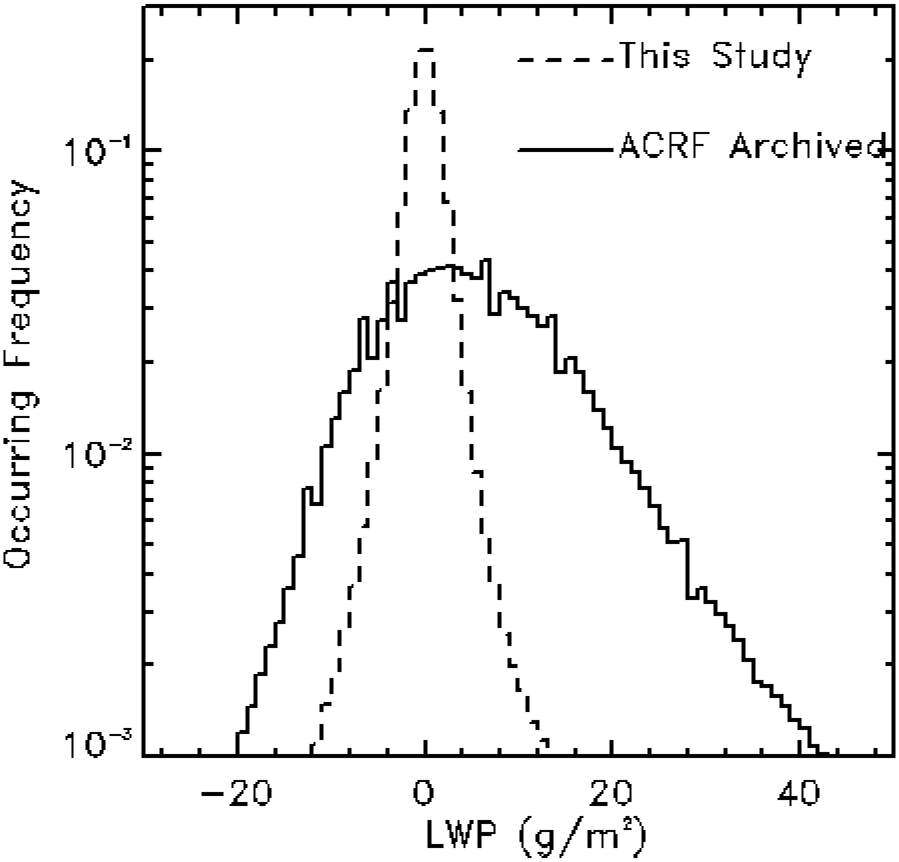


Figure 1. Z. Wang, University of Wyoming, 2010

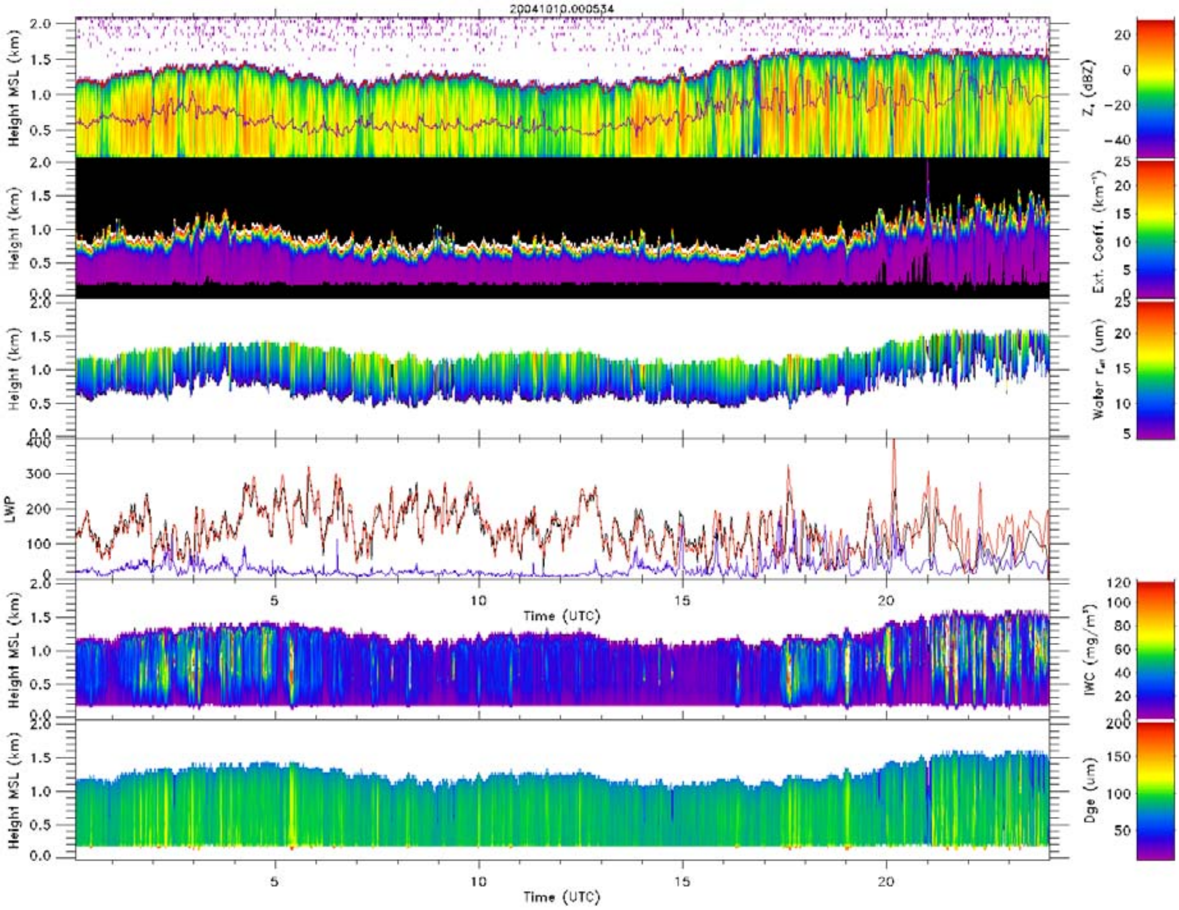


Figure 2. Z. Wang, University of Wyoming, 2010

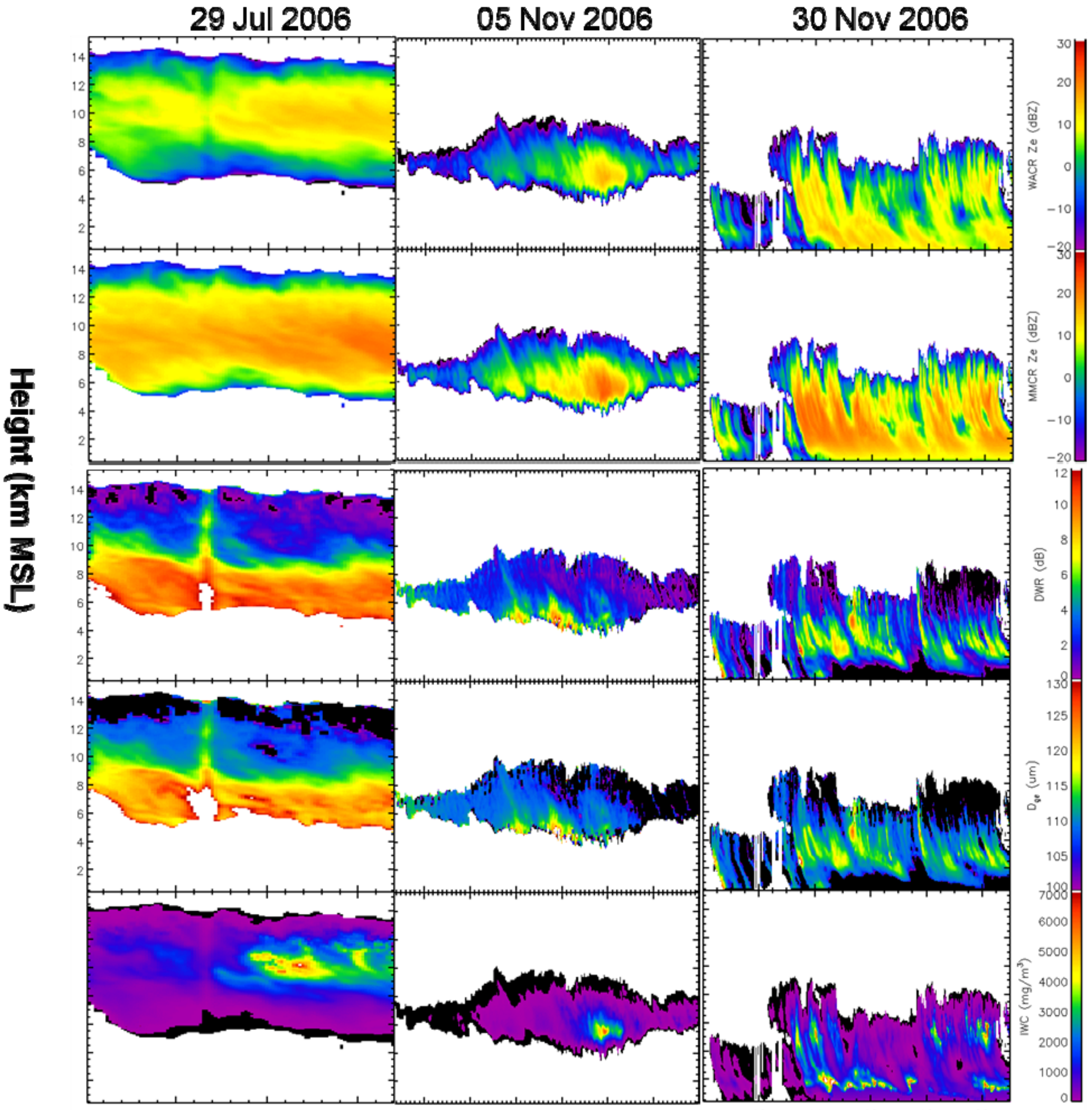


Figure 3. Z. Wang, University of Wyoming, 2010

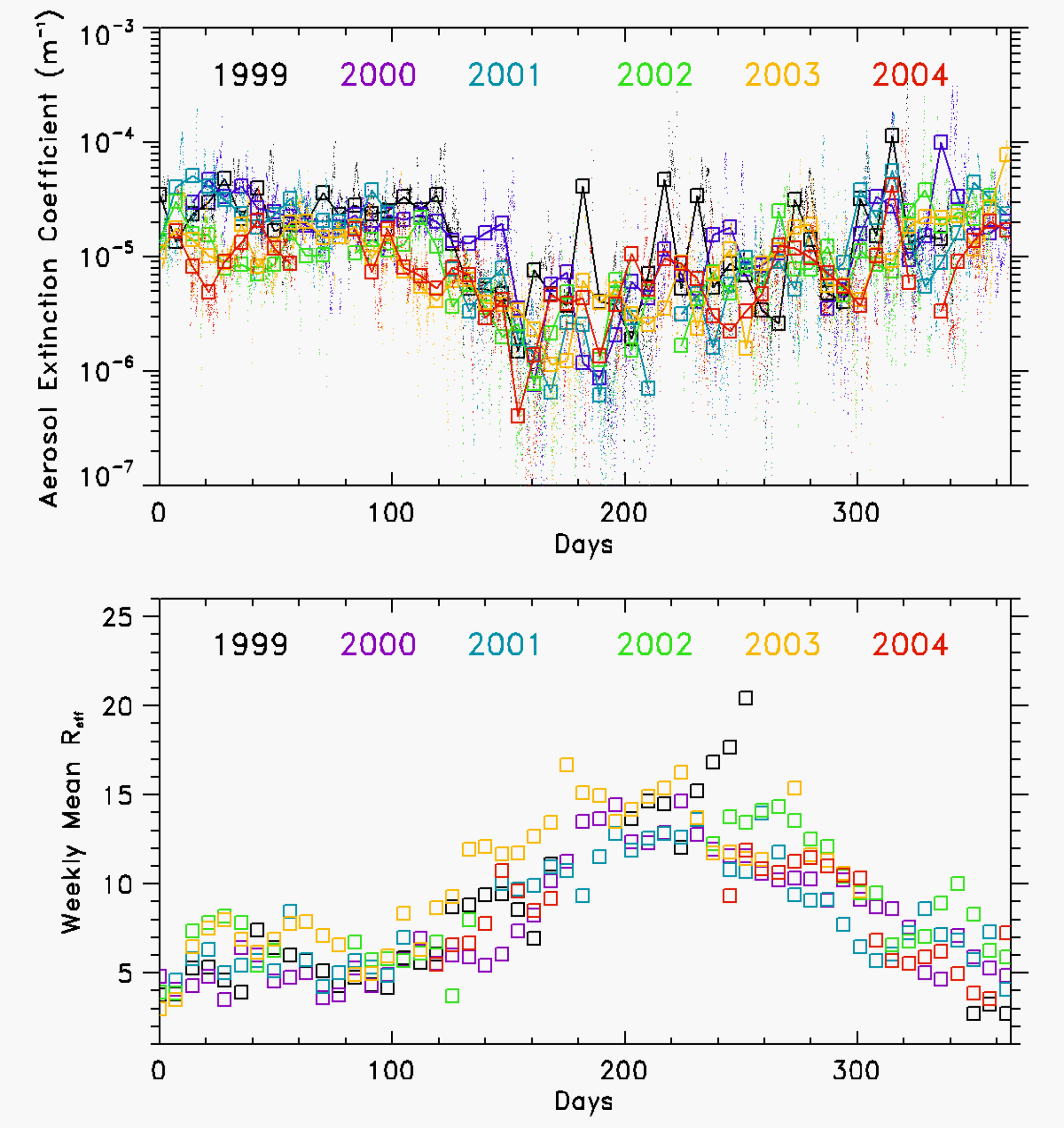
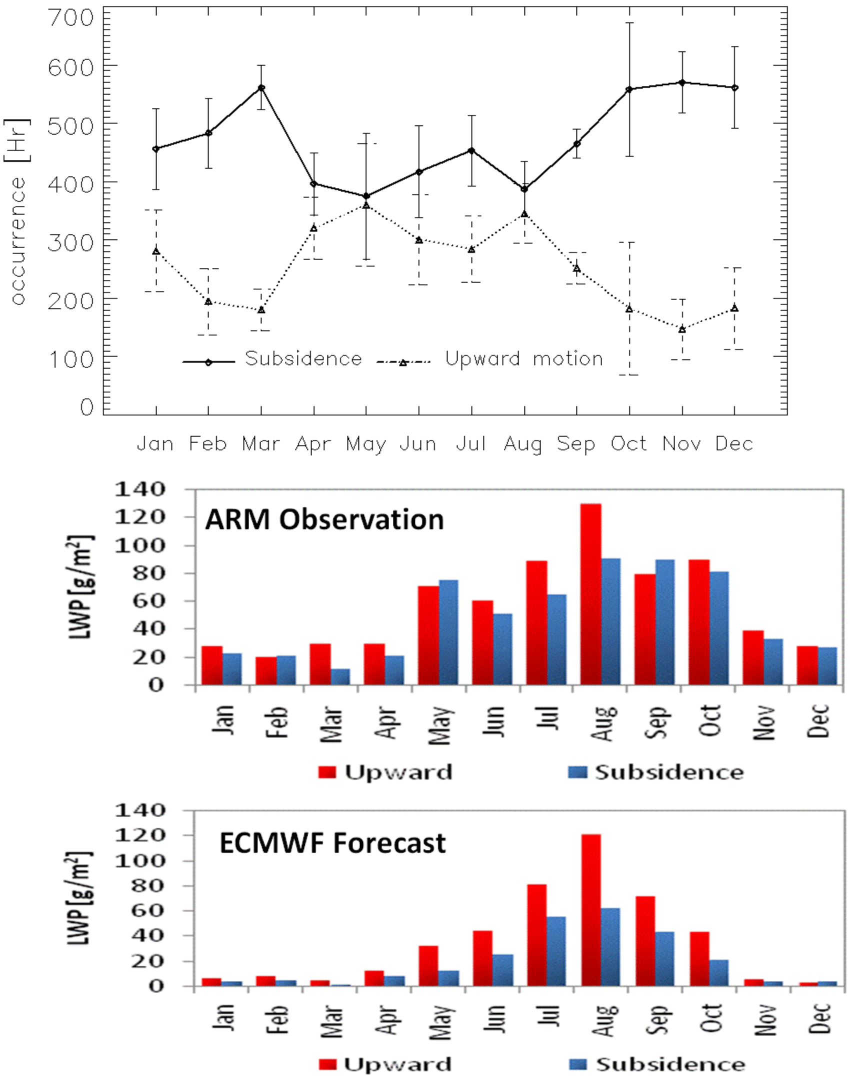


Figure 4. Z. Wang, University of Wyoming, 2010



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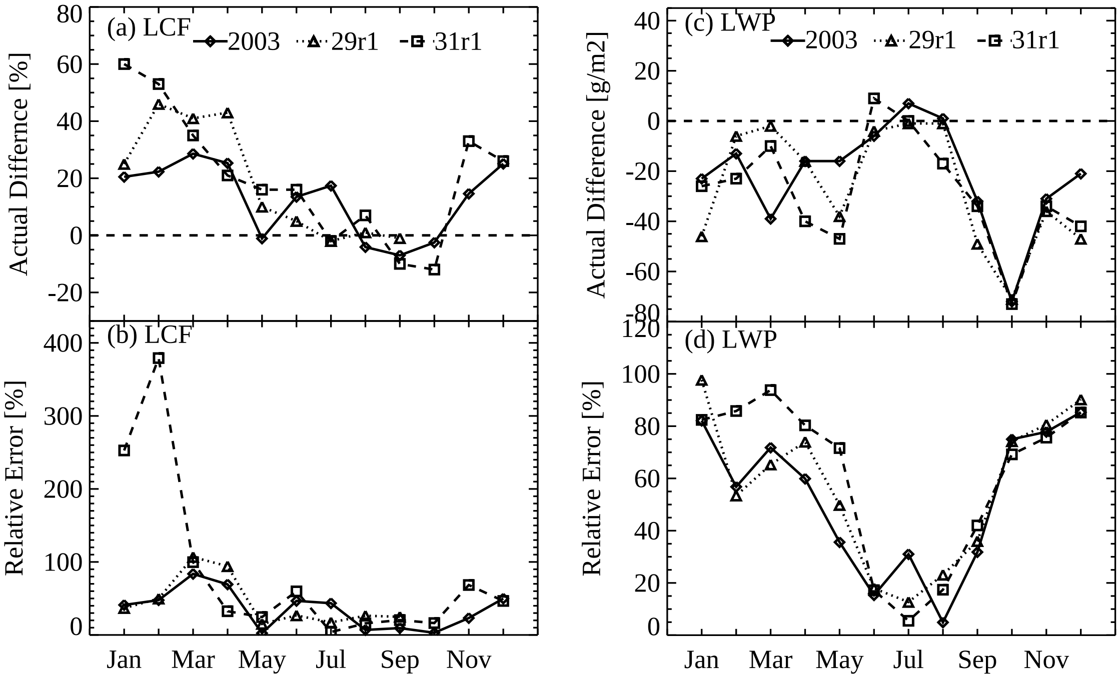

Figure 6. Z. Wang, University of Wyoming, 2010

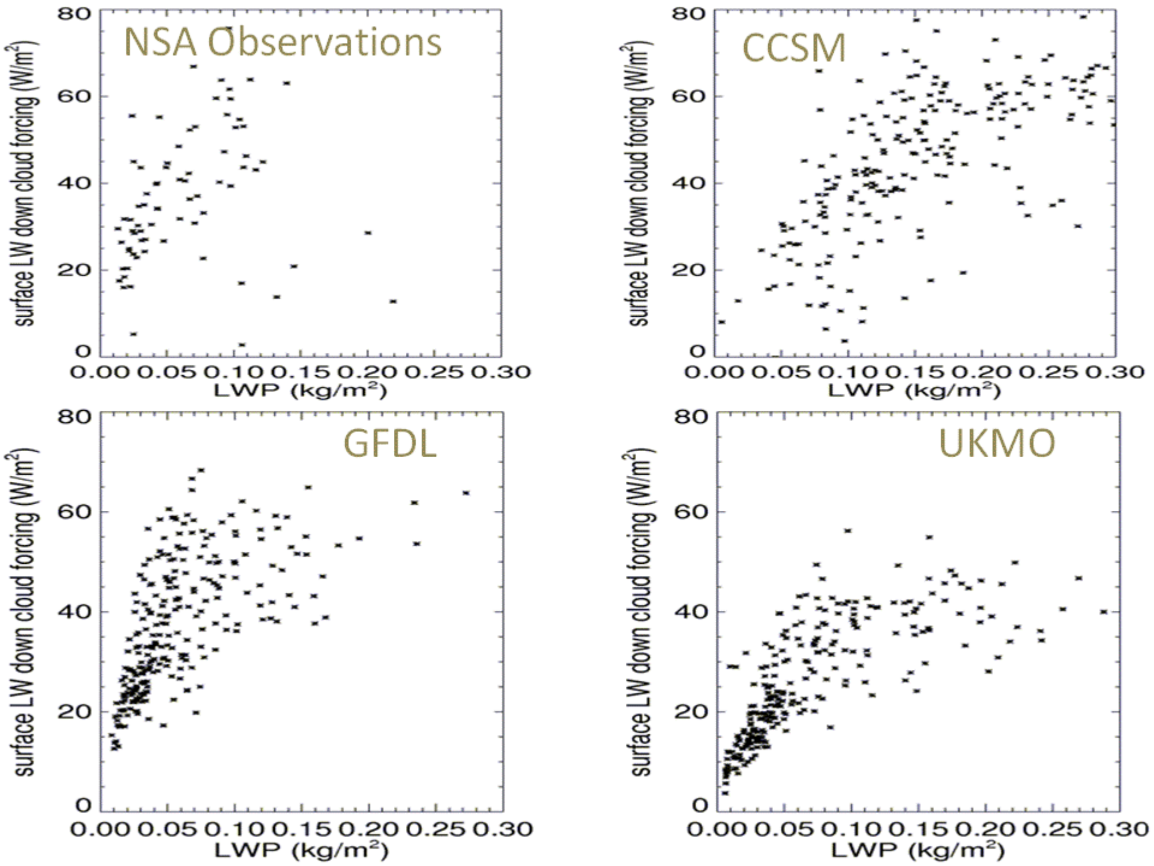

Figure 7. Z. Wang, University of Wyoming, 2010