1. PI: **Z. Wang, University of Wyoming**

2. Title of Research Grant: **Improving Mixed-phase Cloud Parameterization in Climate Model with the ACRF Measurements (**DOE grant: DE-SC0006974)

3. Scientific Goal(s):
   Mixed-phase cloud microphysical and dynamical processes are still poorly understood and their representation in GCMs is a major source of uncertainties in overall cloud feedback in GCMs. Thus improving mixed-phase cloud parameterizations in climate models is critical to reduce the climate forecast uncertainties. This study aims at improving the mixed-phase cloud parameterizations in GCMs with the knowledge learned from the long-term ACRF observations. Three specific objectives are set for the next three-year. 1) With the addition of new ACRF instrumentation (new lidars and scanning cloud radars) from the 2009 ARRA, we will better characterize the ice generation and the growth lifecycle of stratiform mixed-phase clouds, as well as the vertical distributions of aerosol properties which are important for understanding the ice generation, and the microphysical and dynamical properties of mixed-phase clouds. 2) With long-term ACRF observations at the NSA site, we aim at advancing our processes level understanding of aerosol–cloud interactions and other factors in controlling ice generation and ice-liquid mass partition in stratiform mixed-phase clouds. 3) With new knowledge gained from observations, we will focus on improving the representation of heterogeneous ice nucleation and the sub-grid processes which are important for stratiform mixed-phase cloud maintenance in the NCAR Community Atmosphere Model version 5 (CAM5). The improvement of the CAM5 will be done in a close collaboration with Drs. Steve Klein, LNNL and Xiaohong Liu, PNNL.

4. Key accomplishments:
   - An improved retrieval algorithm to provide liquid droplet concentration for drizzling or mixed-phase stratiform clouds.
   - A new ice concentration retrieval algorithm for stratiform mixed-phase clouds.
   - Identified a strong seasonal aerosol impact on ice generation in arctic mixed-phase clouds, which is mainly associated with high dust occurrence during the spring season.
   - Multi-year stratiform mixed-phase cloud dataset developments based on ARM measurements at the Barrow site.
   - The first reliable comparison of liquid mass partition in stratiform and convective mixed-phase clouds.
   - Systematic evaluations of mixed-phase cloud simulations by CAM5

5. Detail Progress Description:

a) An improved retrieval algorithm to provide liquid droplet concentration for drizzling or mixed-phase stratiform clouds

To effectively study arctic mixed-phase clouds and factors controlling their variations, we are refining the multi-sensor mixed-phase microphysical retrieval algorithm to provide liquid droplet concentration and ice crystal number concentration in the stratiform clouds. By properly correcting multiple scattering effects in lidar measurements with lidar depolarization measurements, we show that liquid droplet number concentration in drizzling or mixed-phase stratiform clouds can be derived from lidar derived extinction profile and the adiabatic cloud assumption. Figure 1 shows the comparison of observed and retrieved cloud droplet concentrations (N) based on lidar and in situ probe observations from NSF/NCAR C-130 during the VOCALS experiment. Due to using the same aircraft to collect below clouds and in clouds data, the in situ and retrieved Ns are spatially off up to tens of kilometers, which contribute to some scatterings in Fig. 1. Considering in situ probe uncertainties, Fig. 1 indicates a good accuracy of retrieved N. The algorithm paper is presented in Snider et al. (2016, JAS, in press).

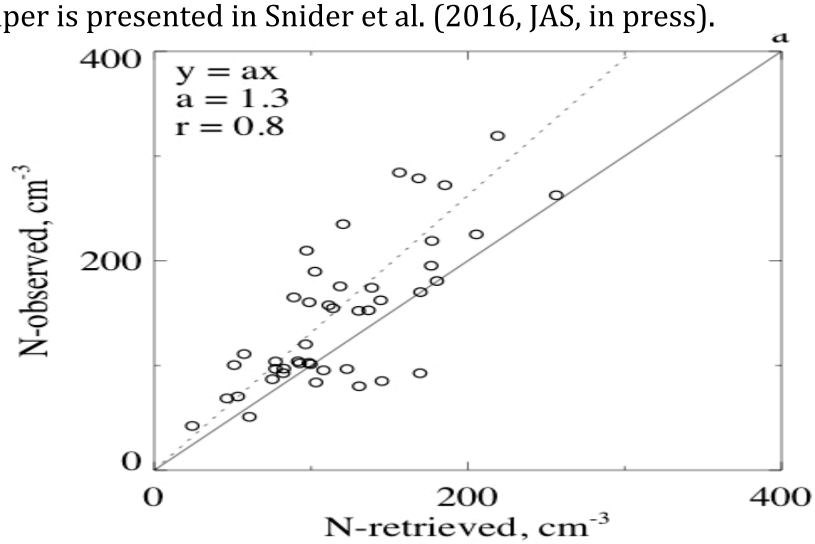


Figure 1. Comparison of observed and retrieved cloud droplet number concentrations for drizzling stratocumulus clouds during the VOCALS. Each data point represents means of retrievals from a below cloud leg and nearby in cloud measurements.

b) A new ice concentration retrieval algorithm for stratiform mixed-phase clouds

Another important cloud property to better understand aerosol-cloud introductions in stratiform mixed-phase clouds is ice concentration. A new algorithm is developed by taking advantages of simple dynamic environments of stratiform mixed-phase clouds and using radar measurements to retrieve ice crystal concentration. This is also a critical step to validate and improve cloud microphysical parameterization. To achieve this goal, we need to be able to model the strong temperature dependent of ice crystal growth related to ice crystal habit changes. To link with radar measurements, we have to consider the growth and falling nature of ice in these clouds at least. Because of weak updraft in these clouds, ice crystals are mainly generated near cloud top (due to the coldest temperature), then grow big and fall out of the mixed-phase cloud layer. Thus, a 1-D model is developed to capture this general feature by considering the temperature dependent ice crystal shapes and corresponding growth rates and falling speeds. This will allow us to model vertical distribution of radar reflectivity factor (Z_e). Figures 2 and 3 show modeled and MMCR observed Doppler velocity and Z_e profiles at different cloud temperature ranges. It is clear that our improved 1-D model can capture the observed vertical trends of Doppler velocity and Z_e. The algorithm is documented in Zhang et al. (2014).

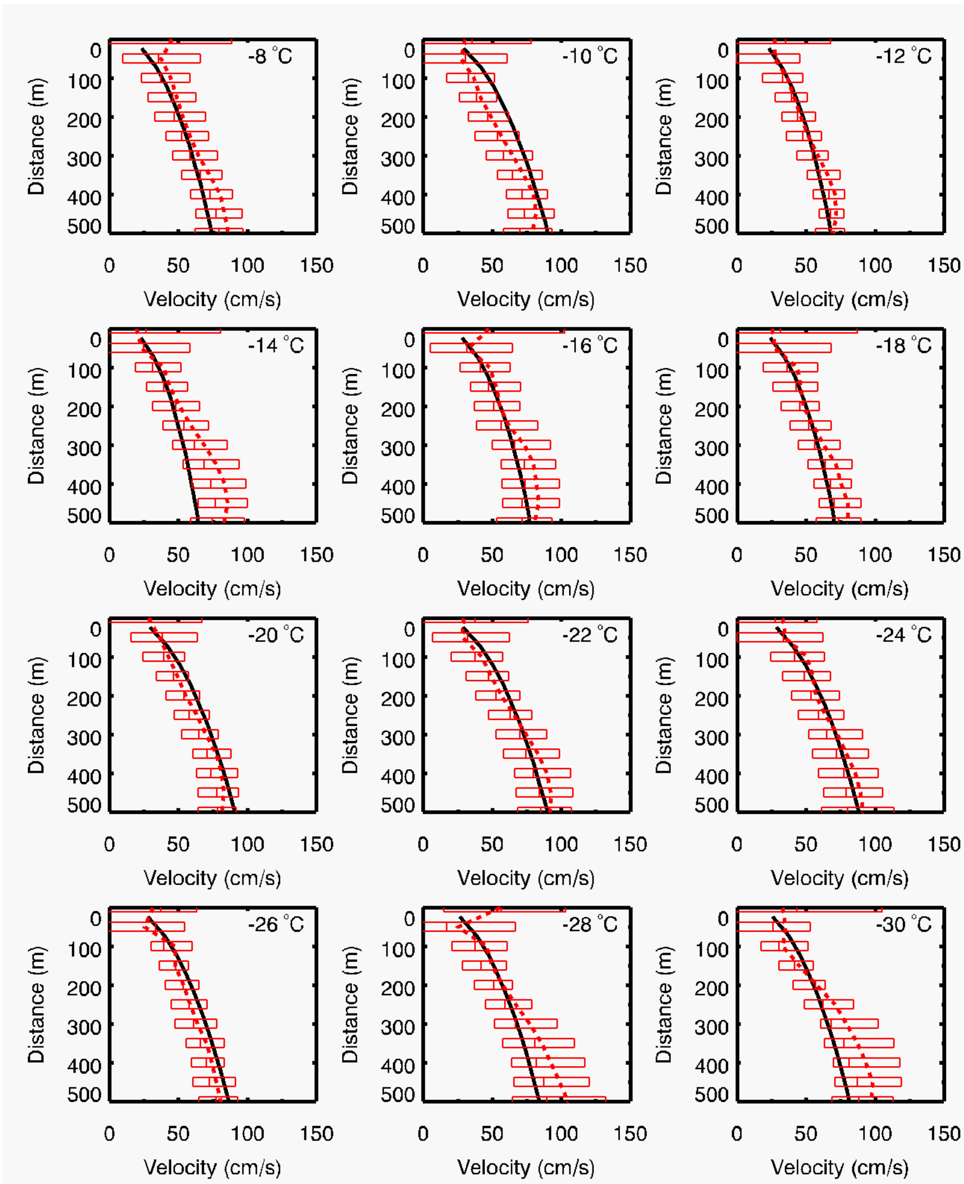


Figure 2. Comparisons of ice crystal falling velocity from 1-D ice growth model simulations (black solid lines) with measured mean MMCR Doppler velocity (red dashed lines) at each cloud top temperature (CTT). The red boxes represent the 25%, 50%, and 75% of MMCR measurements at each CTT.

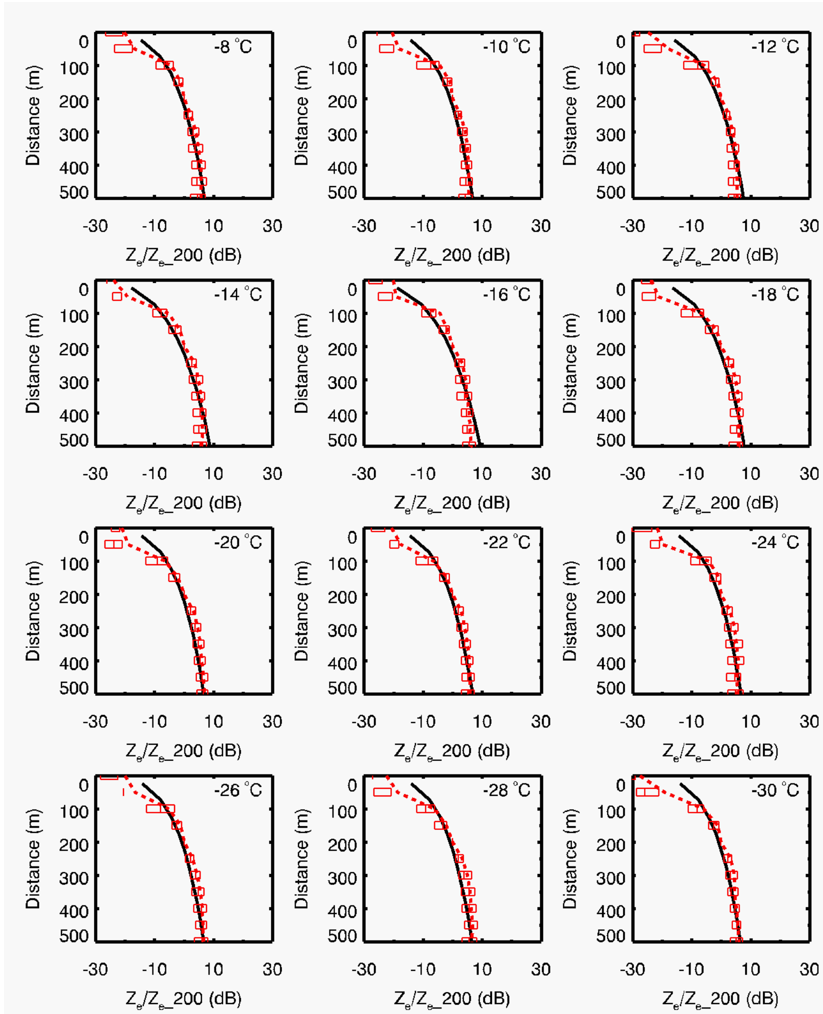


Figure 3. Comparisons of normalized Z_e profiles along fall trajectory from 1-D ice growth model simulations (black solid lines) with 4 years of MMCR measurements (red dashed lines) at each CTT. The red boxes represent the 25%, 50%, and 75% of MMCR measurements at each CTT.

The retrieved ice number concentrations are evaluated using collocated airborne in situ and radar measurements and three-dimensional cloud-resolving model simulations with a bin microphysical scheme. Figure 4 shows the comparison of the retrievals from airborne radar measurements and in situ cloud probe measurements. The statistical evaluations show that the retrieved ice number concentrations in the stratiform mixed-phase clouds have an uncertainty of a factor of 2, which still provide important observational constrain for modeling considering that there are over an order of magnitude of ice concentration variations among different parameterizations.

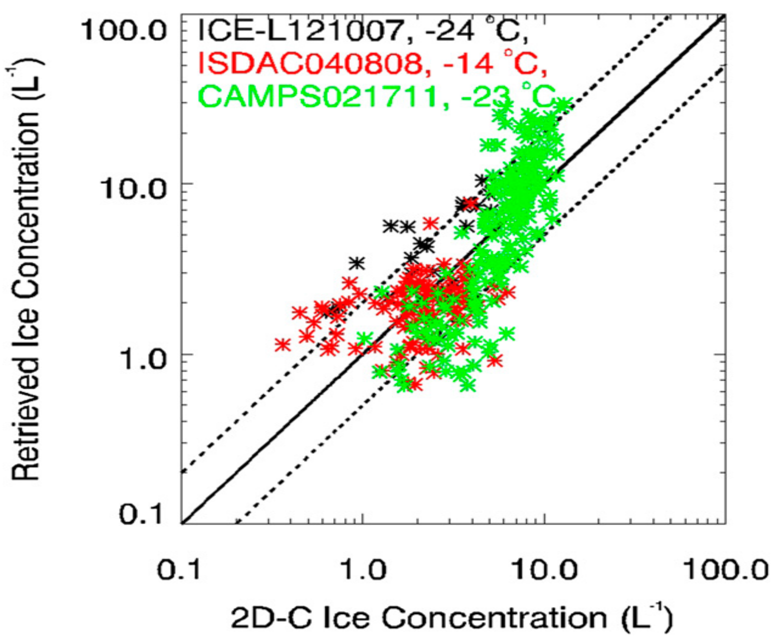
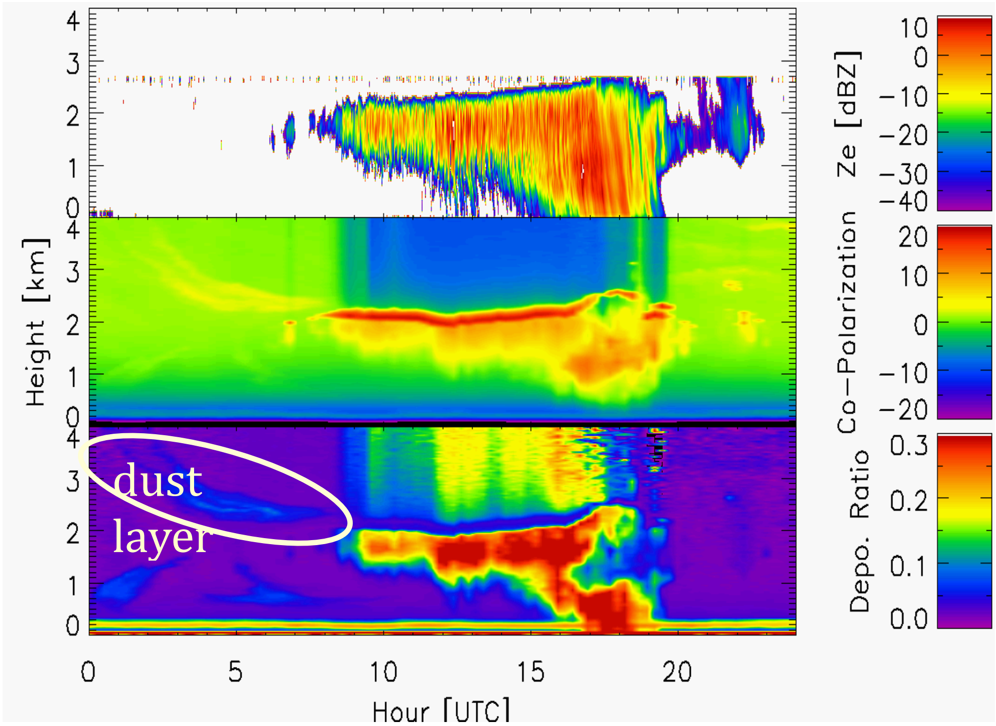


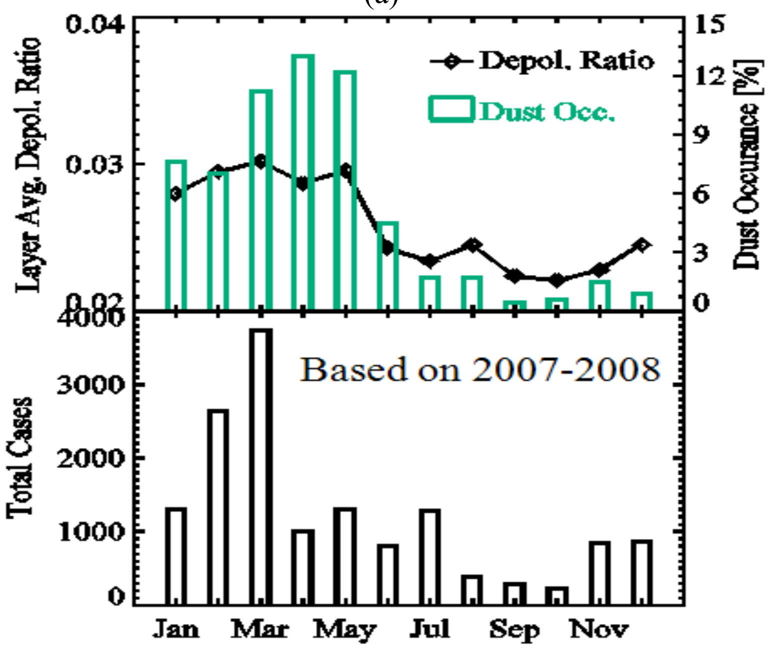
Figure 4. Comparisons of the retrieved Ni with 2D-C measurements for the three SMC systems during ICE-L (black), ISDAC (red), and CAMPS (green) field campaigns. The legend on the top left indicates the field campaign name, date, and mean CTT. The dashed lines are the factor-of-2 lines.

c) Identified a strong seasonal aerosol impact on ice generation in arctic mixed-phase clouds, which is mainly associated with high dust occurrence during the spring.

To effectively link aerosols, especially surface measurements, with mixed-phase cloud properties, it is important understand vertical distribution of aerosols and their spatial inhomogenity. Meanwhile boundary layer process and property are important for boundary layer mixed-phase cloud evolution. For this purpose, we explore MPL data for boundary aerosol characterization and use aerosol distributions to determine atmospheric Boundary Layer Height (Luo et al. 2013). Figure 5 illustrates the spatial and temporal variability of dusty aerosol occurrence at the Barrow site based on MPL measurements. Statistically, dust occurs more during the spring season at the BSA site. These dust aerosols, transported long-range from dust source regions, have large potential impacts on arctic mixed-phase cloud properties. The observed seasonal variations of liquid-ice mass partition around the NSA site as highlighted in Fig. 6 show significant different temperature dependent than other seasons, which is consistent with the high dust occurrence.



(a)



(b)

Figure 5. (a) A case to show spatial distribution of dusty layer (identified based on MPL depolarization) observed at the NSA site and their connection with stratiform mixed-phase clouds. (b) Seasonal variations of dusty aerosol occurrences.

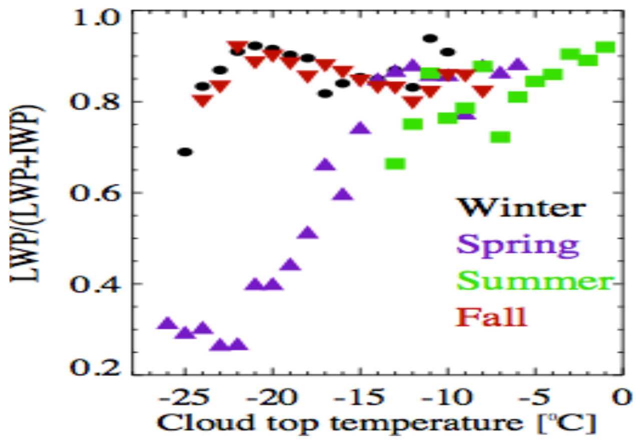


Figure 6. Seasonal variations of ice-liquid mass partition [LWP/(LWP+IWP)] as a function of cloud top temperature based on multi-year retrievals at the Barrow site. Results show that the spring season has a distinct ice-liquid mass partition, a sharp decrease of at temperature around -15°C in arctic mixed-phase clouds, which is closely linked with high occurrence of dust aerosols in the region.

Dust aerosols have been regarded as effective ice nuclei (IN), but large uncertainties regarding their efficiencies remain. To support multi-sensor observation results at the Barrow site, satellite measurements were further analyzed to quantify dust impacts on ice generation in stratiform clouds**.** Four years of collocated CALIPSO and CloudSat measurements are used to quantify the impact of dust on heterogeneous ice generation in midlevel supercooled stratiform clouds (MSSCs) over the 'dust belt' and the corresponding southern hemisphere region (Zhang et al. 2012). The results show that the dusty MSSCs have an up to 20% higher mixed-phase cloud occurrence, up to 8 dBZ higher mean maximum Ze (Ze_maxm, see Fig. 7), and up to 11.5 g/m^2 higher ice water path (IWP) than similar MSSCs under background aerosol conditions. Assuming similar ice growth and fallout history in similar MSSCs in terms of CTT and LWP, the significant differences in Ze_max between dusty and non-dusty MSSCs reflect ice particle number concentration differences. Therefore, observed Ze_max differences indicate that dust could enhance ice particle concentration in MSSCs by a factor of 2 to 6 at temperatures colder than -12°C and depending on CTT. Figure 7 also shows large regional differences of dust impacts, which are caused by different large dust particle concentrations and chemical compositions based on preliminary results.

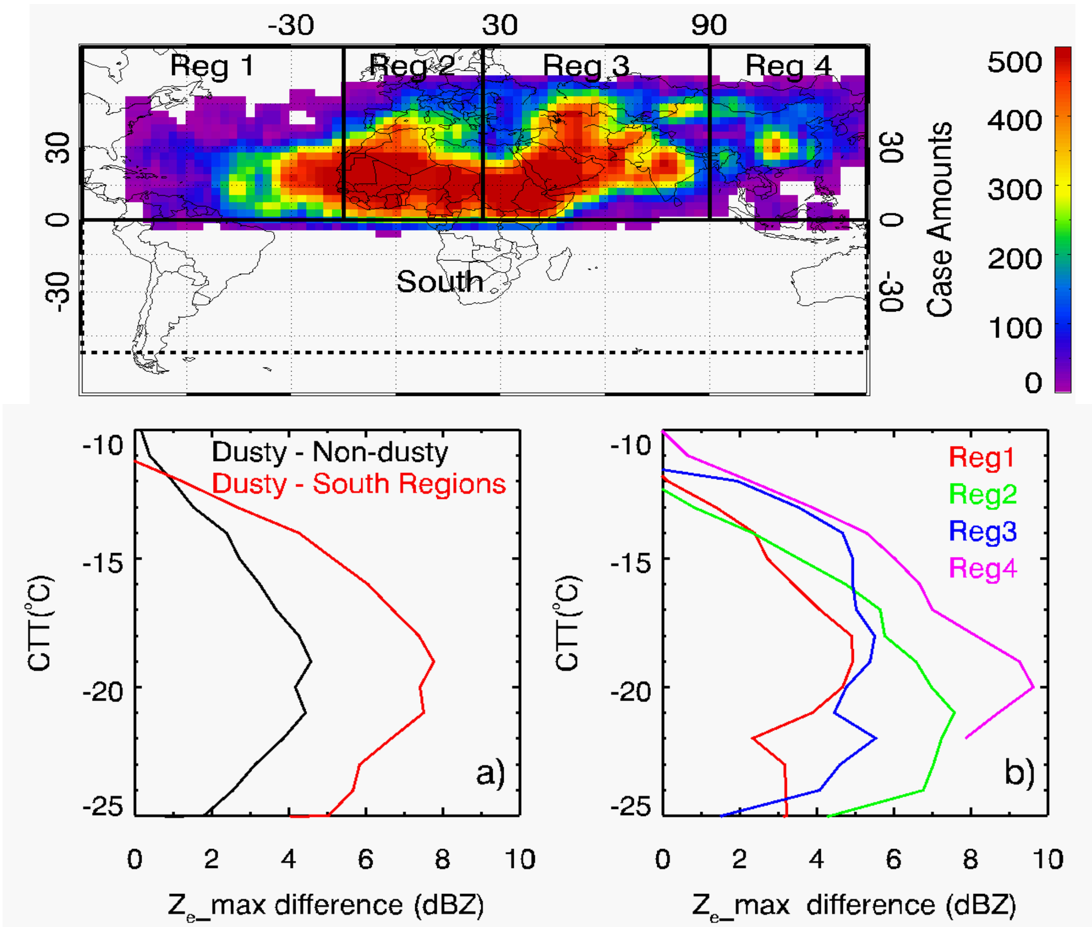


Figure 7. Upper: the distribution of dusty MSSCs and the locations of four sub-regions. Lower: (a) Z_e_max differences between dusty, non-dusty and 'South Regions' MSCs in terms of CTT; (b) Z_e_max differences between dusty and 'South Regions' MSCs for the four sub-regions.

d) Multi-year stratiform mixed-phase cloud dataset developments based on ARM measurements at the Barrow site

Other than new algorithms discussed above, we evaluated the performance of a lidar-radar algorithm (Wang and Sassen 2002) for cloud ice water content in the stratiform mixed-phase clouds by using Remote sensing and in-situ measurements made by the instruments aboard University of Wyoming King Air (UWKA) aircraft during the Storm Peak Laboratory Cloud Property Validation Experiment (STORMVEX) and the Storm Colorado Airborne Multi-phase Cloud Study, 2010-2011 (CAMPS). Results indicated that lidar-radar retrieval algorithms developed for cirrus cloud can be used for ice virga or precipitation retrievals in stratiform mixed-phase clouds by avoiding horizontally oriented ice crystals, which can be identified by lidar power and depolarization measurements (Khanal and Wang 2015).

We applied a suite of multi-senor algorithms to long-term ARM observations to provide a complete dataset (LWC and effective radius profile for liquid phase, and IWC, Dge profiles and ice concentration for ice phase) to characterize arctic stratiform mixed-phase clouds. This cloud dataset, together with the aerosol properties from other instruments, will offer a powerful dataset for the process studies and model evaluations of Arctic stratiform mixed-phase clouds. Figure 8 shows the seasonal variations of the mean ice concentrations in stratiform mixed-phase clouds based on KAZR measurements from 2011 to 2014. Clearly, there are large seasonal ice concentration variations at temperature warmer than -30 °C. For clouds with top temperatures warmer than -15 °C, the ice concentrations are the highest during MAM. This could be associated with the higher aerosol concentrations in MAM. The results indicate that simple temperature dependent ice concentration parameterizations, which are still widely used in many state-of-art weather and climate models, are not able to capture the natural variations. This will limit our capability to simulate cloud feedbacks in climate models. Therefore it is important to link aerosols with ice generations in models to better capture the natural cloud variations. The observations at the NSA site offer an opportunity to link aerosols with observations for further process studies and model evaluations.

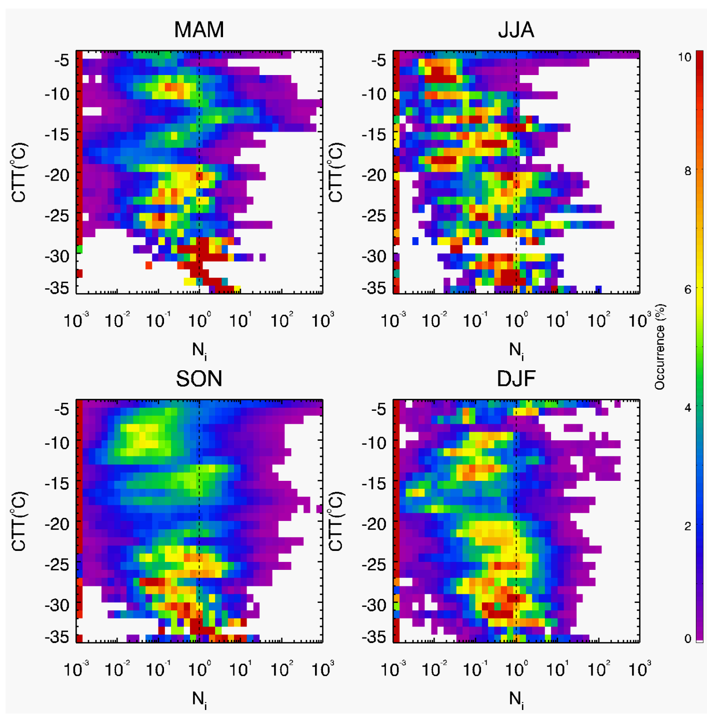


Figure 8. The seasonal variations of ice concentration distributions as a function of cloud top temperature (CTT). The occurrence is normalized for each CTT bin. The results are based on single layer mixed-phase clouds measured by KAZR during 2011-2014.

Figure 9 shows the variations of the liquid-ice mass partition in arctic stratiform mixed-phase clouds as a function of the cloud top temperature and the layer mean ice concentrations. The results suggest that ice concentration is a more critical parameter in controlling liquid-ice mass partition than temperature.

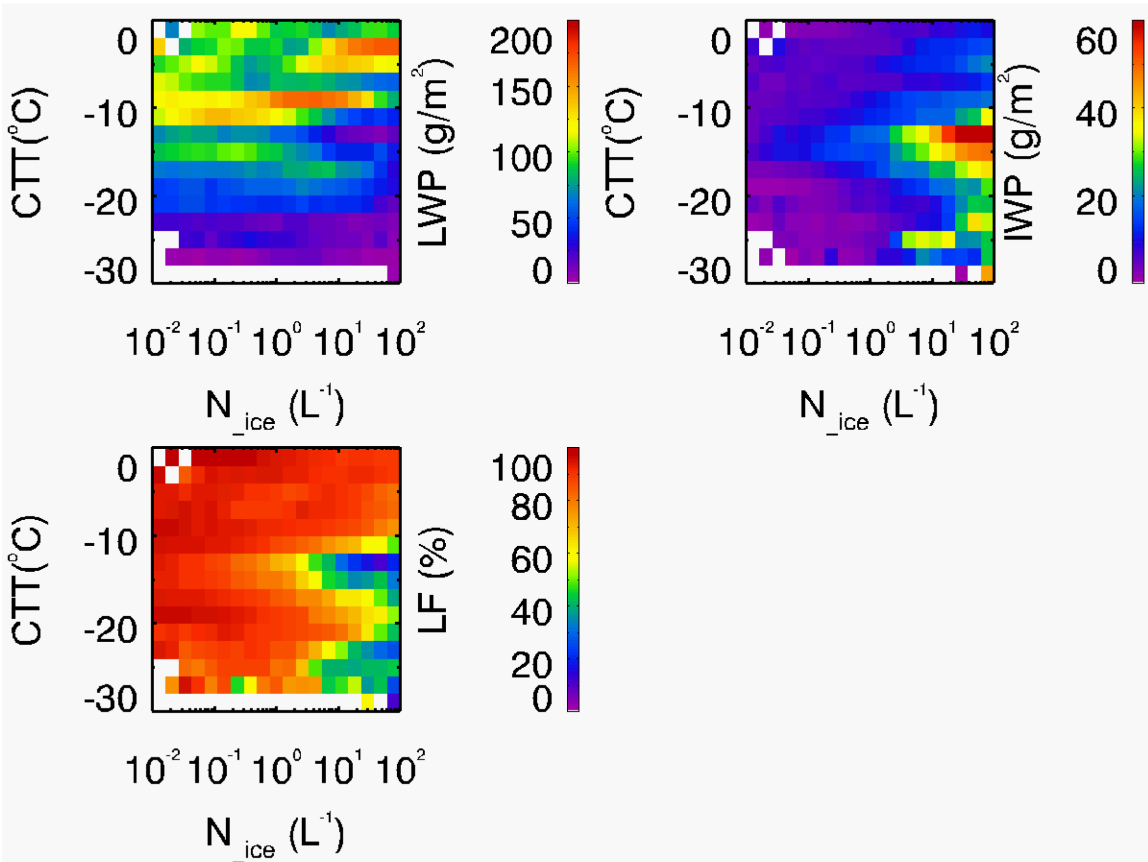


Figure 9. Temperature-dependent liquid and ice water paths and Liquid Fraction (LF = LWP/(LWP+IWP**)** in the mixed-phase layer as a function of the layer mean ice concentration for the stratiform mixed-phase clouds observed at the Barrow site.

One challenging in this part of study was the inconsistent radar calibrations among different generation radars. We found that there are large systematic calibration errors over the whole period in cloud radar measurements. We discussed this issue with ARM radar team. This delayed our efforts to release the dataset as the PI product. Now ARM radar team released recalibrated radar data, we will reprocess all retrievals and make them available for others.

e) Comparison of liquid-mass partition in stratiform and convective mixed-phase clouds

Due to the different dynamics in stratiform and convective mixed-phase clouds, it is expected that there are systematic differences in the liquid-ice mass partitioning as a function of temperature between the two types of mixed-phase clouds. However, there is no systematic study. We developed a new approach to determine the liquid and ice water content based on airborne in situ measurements, which allows us to study the liquid-ice mass partitioning in convective clouds at different developing stages (Yang et al. 2016) and compare the differences between stratiform and convective mixed-phase clouds. Figure 10 provides such a comparison. For arctic stratiform mixed-phase clouds, the liquid fraction is based on multi-year multi-sensor retrievals at the Barrow site. During spring, the temperature-dependent liquid fraction is systematically different than those observed in the other three seasons, which could be linked with high dust occurrence during spring at the Barrow site. For tropical maritime convective clouds, liquid fraction is calculated as the ratio of LWC to the total water content based on in situ measurements. The convective cloud life stages (developing, mature, and dissipating) are identified based on Wyoming Cloud Radar measurements onboard the aircraft. It is clear that liquid/ice mass partition in convective clouds strongly depends on the convective cloud life cycles. There are systematic differences in liquid fraction between the stratiform and convective mixed-phase clouds, which could be attribute to different ice generation mechanisms. As a part of ongoing work, we are improving model cloud microphysics, especially ice generation, to simulate the observed differences in Fig. 10

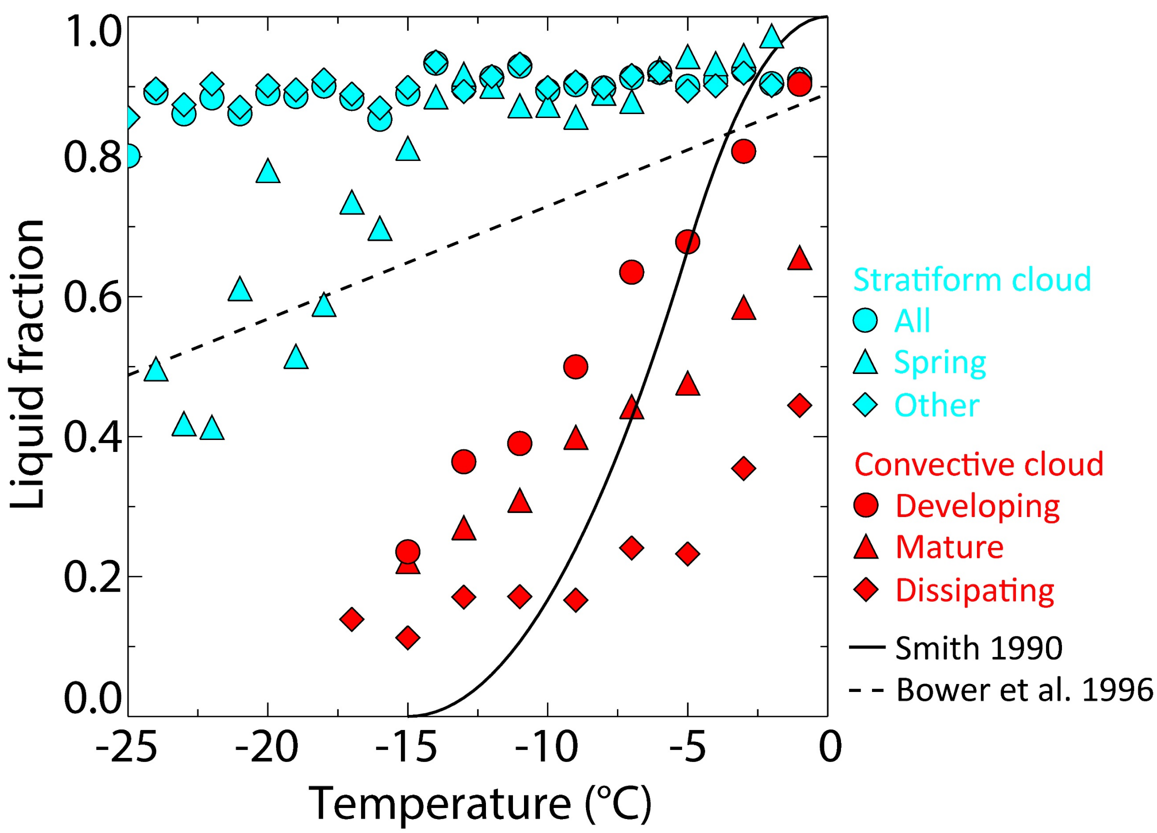


Figure 10: Comparisons of temperature-dependent liquid fractions between the observations from Arctic stratiform mixed-phase clouds and tropical maritime convective clouds.

f) Systematic evaluations of mixed-phase cloud simulations by CAM5

A key to improve mixed-phase cloud simulations is to better constrain ice concentrations. Due to the radar calibration issue at the NSA site, our CAM5 model evaluations are mainly focused on using satellite measurements. We applied the Ze based ice concentration retrieval to satellite observed MSSCs. Figures 11 show the distributions of retrieved ice concentrations under different dusty conditions, which are compared with different parameterizations. The results clearly show large variations in ice concentrations under a given CTT, which indicates that a better understanding of ice concentration variations in association with aerosol property variations is needed. The old parameterizations generally overestimate ice concentrations.

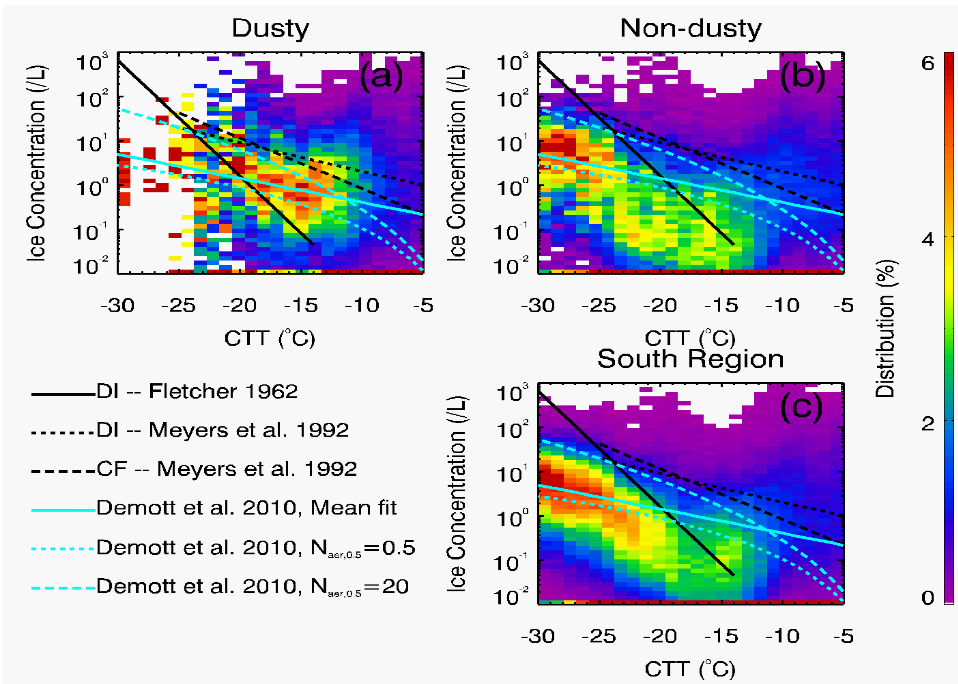


Figure 11. Retrieved ice concentration distributions based on CloudSat radar measurements under different dusty conditions and comparison with different parameterizations.

With three-hourly CAM5 model outputs, we developed an approach to diagnose mixed-phase clouds simulated by models, and then we can compare them with observations. Figure 11 compared compares CAM5 simulated ice partition ratio as a function of cloud top temperature and latitude based on one-year mean results. It is clearly that CAM5 overestimated ice phase contributions, especially in the storm-tracks. This could be attributed to higher ice concentrations in CAM5 (Fig. 12c and 12d). In the default CAM5 setting, ice concentrations parameterizations are parameterized as simple functions of temperatures. It is clear that this type of parameterization is not able to catch the natural ice concentration variations as highlighted in Fig. 11.

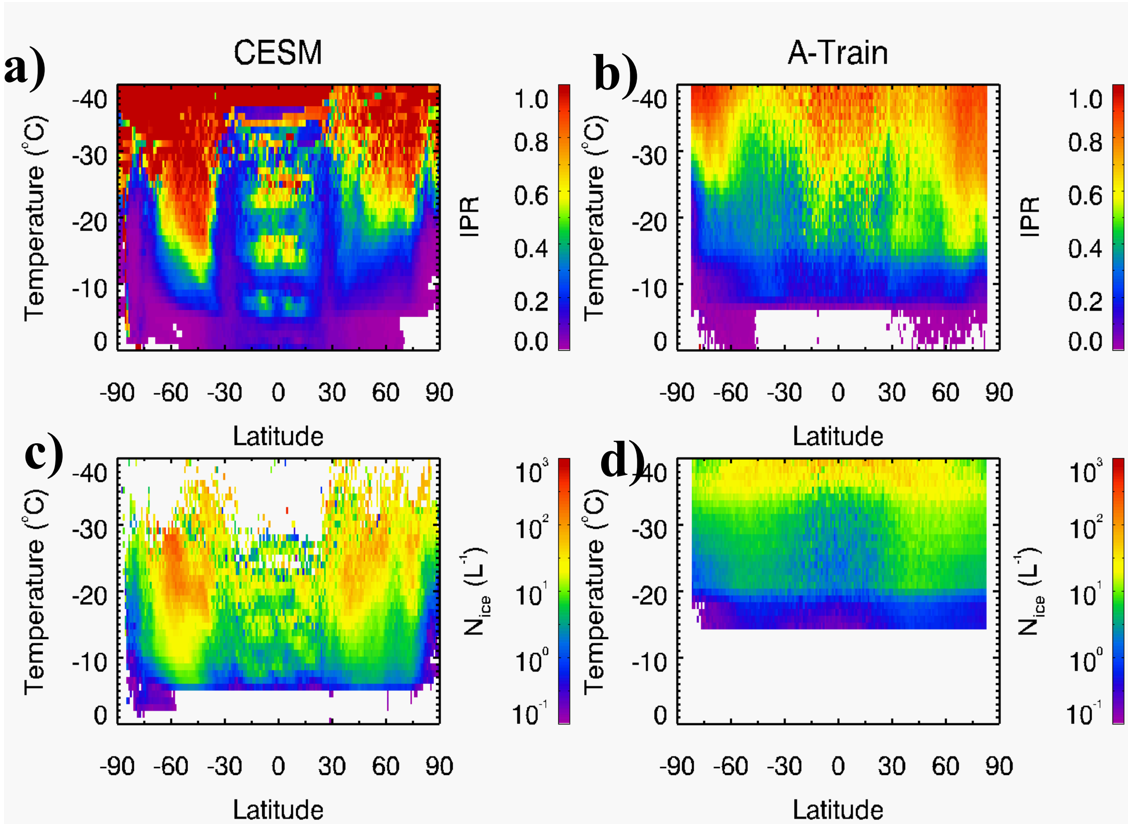


Figure 12. Cloud Ice Partition Ratio (IPR = IWP/(LWP + IWP)) and mixed-phase cloud N_{ice} in terms of cloud top temperatures at each latitude: (a) and (c) for CESM model simulations, (b) and (d) from A-train retrievals. CESM CAM5 model simulations are one-year three-hourly outputs at the grid resolution of 0.9 x 1.25. The A-Train results are single-layer daytime mixed-phase clouds by combining multiple products. N_{ice} retrievals at temperatures warmer -15 ^{o}C are not presented due to the need of further validations

In collaboration with Dr. Liu, we further evaluated CAM5 mixed-phase clouds with an improved ice concentration parameterization (Wang et al. Atmos. Chem. Phys., 14, 10411–10430, 2014). The new parameterization lead to improved mixed-phase cloud simulations in CAM5. We are working on a journal paper to report the new results. These datasets and initial results set the base to further improve the parameterization of ice generations and mixed-phase cloud simulations in climate and weather models.

6. Refereed Publications

Zhao, et al. 2012: Toward understanding of differences in current cloud retrievals of ARM ground-based measurements, *J. Geophys. Res*., 117, D10206**.**

Zhang, D., Z. Wang, A. J. Heymsfield, J. Fan, D. Liu, and M. Zhao: 2012, Quantifying the impact of dust on heterogeneous ice generation in midlevel supercooled stratiform clouds, *Geophys. Res. Lett.*, 39, L18805, doi:10.1029/2012GL052831.

Adhikari, L. and Z. Wang, 2013: An A-train satellite based stratiform mixed-phase cloud retrieval algorithm by combining active and passive sensor measurements, British Journal of Environment and Climate Change, Vol.: 3, Issue: 4 (Oct-Dec)-Special Issue, DOI : 10.9734/BJECC/2013/3055.

Luo, T., R. Yuan, and Z. Wang, 2013:Lidar-based remote sensing of atmospheric boundary layer height over land and ocean, Atmos. Meas. Tech. Discuss., 6, 8311-8338, doi:10.5194/amtd-6-8311-2013, 2013

Zhang, D., Z. Wang, A. Heymsfield, J. Fan, and T. Luo, 2014: Ice Concentration Retrieval in Stratiform Mixed-phase Clouds Using Cloud Radar Reflectivity Measurements and 1-D Ice Growth Model Simulations, *J. Atmos. Sci.*, **71**, 3613–3635.

Khanal, S., and Z Wang, 2015: Evaluation of the lidar-radar cloud ice water content retrievals using collocated in-situ measurements. *Journal of Applied Meteorology and Climatology,* 2015, 2087-2097, DOI: 10.1175/JAMC-D-15-0040.1.

Yang, J., Z. Wang, A. Heymsfield, T. Luo, 2016: Liquid/Ice Mass Partition in Tropical Maritime Convective Clouds, *J. Atmos. Sci.*, (in press).

7. Extended Abstracts and Presentations

1. Adhikari, L. and Z. Wang, 2012: Mixed-phase Cloud Properties Retrieval Using MODIS Reflectances and ARM NSA Ground-based Data. *Proceedings of the third science team meeting of the Atmospheric System Research (ASR) program*, March 12-16, 2012, Arlington, Virginia.
2. Zhang, D., et al., 2012: Quantifying the dust impacts on the ice generation in supercooled stratiform clouds by combining remote sensing and in situ measurements, *16th International Conference on Clouds and Precipitations*, July 30- August 3, 2012.
3. Luo, T., Z. Wang, and D. Zhang, 2013: Comparison of Atmospheric Boundary-layer Structures over Land and Ocean as Observed by ARM Ground-based and Space-based Lidar Measurements, *Proceedings of the fourth science team meeting of the Atmospheric System Research (ASR) program*, March 18-21, 2013 Potomac, Maryland.
4. Zhang D., Z. Wang, A. Heymsfield, and J, Fan, 2013: Ice Concentration Retrieval in Mixed-phase Stratiform Clouds (MSCs) Using Radar Reflectivity and 1D Ice Growth Model, *Proceedings of the fourth science team meeting of the Atmospheric System Research (ASR) program*, March 18-21, 2013 Potomac, Maryland.
5. Wang Z., D. Zhang, M. Zhao, and A. Heymsfield, 2013: Quantifying the Dust Impacts on the Ice Generation in Supercooled Stratiform Clouds, *Proceedings of the fourth science team meeting of the Atmospheric System Research (ASR) program*, March 18-21, 2013 Potomac, Maryland.
6. Zhang et al. 2014: Ice Concentration Retrieval in Stratiform Mixed-phase Clouds Using Cloud Radar Reflectivity Measurement and 1-D Ice Growth Model Simulations. *Presented at 14th Conference on Cloud Physics*, 7-11 July 2014, Westin Copley Place, Boston, MA.
7. Zhang et al., 2014: Seasonal Variations of Ice Number Concentration in Stratiform Mixed-phase Clouds over the ACRF NSA site, *The 5th Atmospheric System Research (ASR) Science Team Meeting*, March 18-21, 2013, Potomac, Maryland.

8. Wang, Z. et al. 2014: Studying Mixed-phase Cloud Properties with in Situ and Remote Sensing Measurements, *The 5th Atmospheric System Research (ASR) Science Team Meeting*, March 18-21, 2014, Potomac, Maryland.
9. Wang, Z. et al., 2014: Observed Strong Ice Generation at Temperatures Warmer than - 8°C and Potential Contribution of Biological Ice Nuclei**.** *Presented at 14th Conference on Cloud Physics*, 7-11 July 2014, Westin Copley Place, Boston, MA.
10. Wang, Z. et al., 2015: Understanding the Liquid-ice Mass Partition in Stratiform and Convective Mixed-phase Clouds, *The 6th Atmospheric System Research (ASR) Science Team Meeting*, March 16-19, 2015, Vienna, Virginia.
11. Zhang, D., Z. Wang, T. Luo, X. Liu, Y. Wang, 2015: Validating Mixed-phase Cloud Simulations from Climate Models with Remote Sensing Measurements, The 2015 Gordon Research Conference (GRC) on Radiation and Climate, July 26-31, 2015, Lewiston, ME.
12. Yang, J., Z. Wang, D. Zhang and X. Liu, 2016: Exploring Observed and Simulated Liquid-ice Mass Partitioning in Stratiform and Convective Mixed-phase Clouds, *The 7th Atmospheric System Research (ASR) Science Team Meeting*, May 2-5, 2016, Tysons, Virginia.