Report

Award No:	DE-SC0011666
Recipient Name:	University of Reading
Project Title:	3D Shortwave Radiative Kernels of Marine Boundary-layer Clouds Using Scanning Radar/Lidar and Array Spectroradiometer
PI Name:	Jui-Yuan Chiu
Project Period:	06/01/2014 – 05/31/2017 with a no-cost extension to 05/31/2018

1. Summary of research outcome

**** Studying processes of aerosol-cloud-rain-radiation interactions***

1.1 3D ENCORE – cloud retrievals developed for ARM scanning cloud radar measurements

The new ARM scanning radars provide a unique opportunity to make robust 3D cloud observations. To take full advantage of the ARM new scanning radar measurements, **Paper [1]** developed a novel ENsemble ClOud REtrieval (ENCORE) method to provide 3D fields of cloud water content and droplet size in both overcast and broken cloud conditions. The retrieval uncertainty is fully characterized and accounted for 3D radiative effect.

Using ARM Mobile Facility measurements at the Azores in 2009 as an example, **Fig. 1** shows 3D cloud retrievals for overcast stratocumulus and challenging shallow cumulus. For the stratocumulus case, ENCORE shows good agreement with independent retrievals of liquid water path along the radiance track from the two-channel microwave radiometers with an error of 20 g m^{-2}, which is comparable to retrieval uncertainty. Interestingly, for the shallow cumulus case, microwave radiometers have difficulty in capturing such clouds that have low water path and highly heterogeneous structure. This highlights that the introduction of the new scanning radars can greatly enhance cumulus observations.

These new scanning cloud radar observations and the new retrieval method open the door to many new lines of research. These lines include improved droplet number concentration in warm clouds (**Paper [10]**), improved drizzle observations (**Paper [3]**) and helping unravel the influence of aerosol on clouds in both a macro- and micro-physical sense (**Paper [7] and [8]**). More details are provided next.

1.2 Retrieving simultaneous drizzle/cloud properties from MAGIC for understanding warm rain formation

ARM's longstanding cloud radar observations have proved invaluable in advancing our understanding of cloud microphysical processes, but they have been limited to non-precipitating clouds. For precipitating clouds, drizzle and large hydrometeors dominate radar returns and thus obscure the retrieval of cloud properties. Since drizzle plays a profound role in determining cloud lifetime and structure in marine

boundary layer clouds, **Paper [3]** developed an adaptation to ENCORE to overcome this hurdle and characterized the vertical structure of droplet size and water content of both cloud and drizzle simultaneously throughout the cloud during the MAGIC campaign in the northeast Pacific. Applications of 1D ENCORE are diverse, including investigations into precipitation formation, and aerosol effects on cloud microphysical properties, as shown next in sections 1.3 and 1.4, respectively.

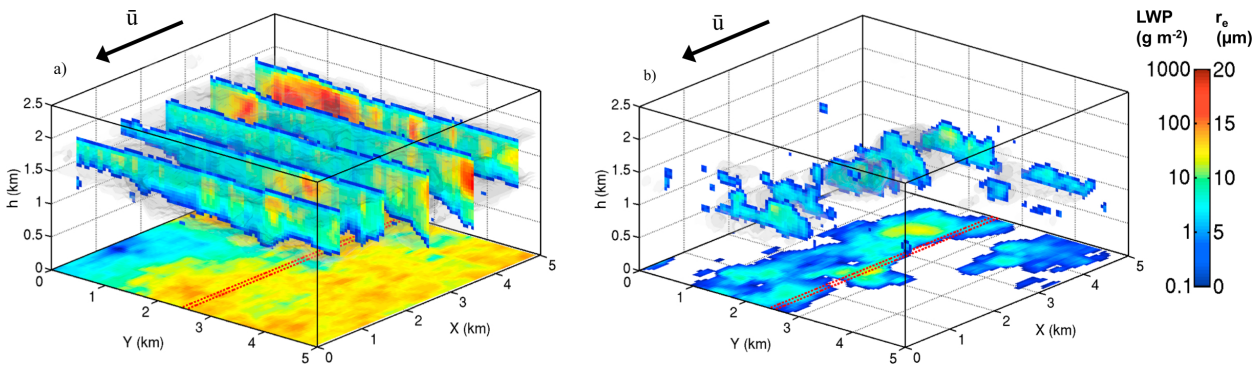

Figure 1. Retrieved cloud fields for (left) stratocumulus case and (right) cumulus case, with 3-D liquid water content plotted as grey isosurfaces, slices of 3-D effective radius (re) plotted along the Y axis and liquid water path (LWP) plotted at the surface. The mean wind (u) direction is shown by the black arrow, while the track of radiances along Y = 2.5 km is shown by the red dashed line.

1.3 Evaluating drizzle formation parameterization using ensemble cloud retrievals

Drizzle, common in marine boundary-layer clouds, plays a crucial role in the microphysical, thermodynamic and dynamic processes that determine cloud structure and properties. Consequently, our ability to model drizzle has a significant impact on understanding and quantifying cloud feedbacks. However, many global models continue to produce drizzle too frequently by a factor of 1.5–2 at cloud base, and likely too heavily in the marine stratocumulus regime. This common model deficiency clearly calls for stronger observational constraints, but progress has been difficult due to a lack of appropriate coincident cloud/drizzle measurements. The entwined nature of clouds and precipitation also compounds the problem further. The new ENCORE retrieval from section 1.1 provides information on in-cloud rainwater content, allowing us to directly constrain process rates of warm rain formation.

Rain formation in warm clouds (i.e., in the absence of ice-phase particles) involves processes of activation, condensation/evaporation, collision–coalescence, and sedimentation. Among these processes, we focus on rain production via the coalescence process, namely autoconversion that produces rainwater by the coalescence of cloud droplets, and accretion that produces rainwater by the coalescence between cloud droplets and raindrops. Constraining these processes mainly involves two tasks. Firstly, we applied 1D ENCORE to measurements from the AMF Azores deployment, and evaluated our retrieval against those from the Parametric Time domain model (PTDM) method in collaboration with Prof V. Chandrasekaran at Colorado State University. The PTDM method decomposes cloud and drizzle spectra using radar reflectivity and Doppler spectra, which is completely independent from 1D ENCORE and thus suitable for evaluations. We have found that in general, separation between cloud and drizzle in 1D ENCORE works well, particularly in the lower part of cloud layers, but

cloud/drizzle retrieval remains quite noisy near cloud tops. Secondly, these retrievals are used to calculate the total coalescence rate (i.e., the summation of autoconversion and accretion). Using retrieval only near cloud base where accretion dominates the total coalescence rate, we have found that the accretion can be constrained and approximated as:

$$\left(\frac{\partial q_p}{\partial t}\right)_{ac} = 3.4\left(q_c q_p\right)^{1.06}, \tag{1}$$

where q_c and q_p are cloud and precipitation mixing ratio, respectively. **Figure 2** shows that the estimated accretion rates from equation (1) have a good correlation to the observed process rates. Compared to the commonly used Khairoutdinov-Kogan (KK) parameterization, the exponents between two parameterizations are almost the same, but the newly estimated scaling factor is almost 20 times smaller than the KK value.

To estimate autoconversion rate, we are in a progress of improving our minimization in order to obtain robust and stable solution. We have found that the standard minimization methods and machine-learning like methods would fail because of the highly non-linear nature of autoconversion, but we have developed a minimization method and achieved some success on satellite data. We are refining our ARM dataset further and will report our finding in journal papers.

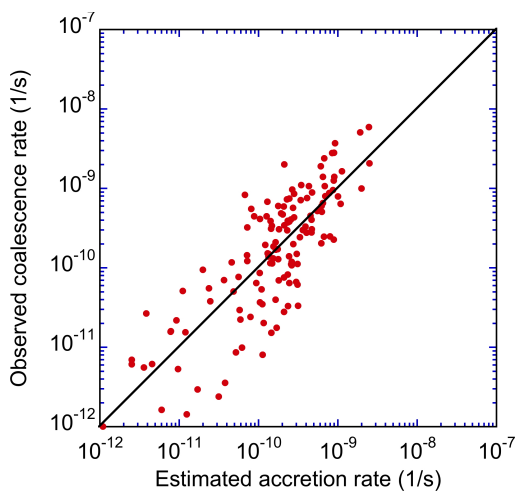

Figure 2. A scatter plot of the observed versus the estimated accretion rates.

1.4 Assessing cloud-aerosol interactions using MAGIC observations

Marine boundary layer clouds remain a primary source of uncertainty in quantifying anthropogenic radiative forcing. **Paper [8]** used the ship-based retrieval from section 1.1 to investigate the covariability between marine low cloud microphysical and aerosol properties. It is found that the aerosol-cloud-interaction from the ship-based observations along transects between Los Angles and Hawaii is high and near the physical upper limit of 1.0. Encouragingly, this value is consistent to the estimations from the overpass satellite observations in the same regime, and from aircraft observations taken in the eastern Pacific, especially for well-mixed boundary layer conditions.

1.5 Advancing understanding of warm cloud properties using unexploited solar background signals in ARM lidar measurements

Low-altitude boundary layer clouds strongly influence global climate through their impact on Earth's radiation and hydrological cycle. Long-term global measurements are therefore crucial for providing direct observational constraints to improve our knowledge of cloud and precipitation formation, and to better represent these clouds in weather and climate models. While ARM data have been extensively used to study variations of liquid water path, cloud base height, cloud fraction, and cloud radiative forcing, surprisingly, little attention is given to the interdependence between cloud macrophysical, microphysical and optical properties, which are actually strongly linked to the stages of warm cloud and precipitation evolutions.

To enhance ground-based observations for studying the interdependence of cloud properties, **Paper [2]** introduced a novel retrieval method that exploits the solar background signals previously treated as noises and removed in lidar measurements. Combining these new retrievals with radar and microwave observations at the ARM Oklahoma site during 2005–2007, we have found that LWP and geometric thickness increase and follow a power-law relationship with cloud optical depth regardless of the presence of drizzle. In contrast, droplet effective radius shows a negative correlation with optical depth in drizzling clouds and a positive correlation in non-drizzling clouds, where, for large optical depths, it asymptotes to 10 µm. More importantly, our results suggest that having lower cloud droplet concentrations will help overcome the lack of liquid water (i.e., fuel for precipitation) to produce drizzling clouds with low optical depths.

We later on extended these retrievals to Azores and Barrow sites, leading to **Paper [4]** and one of the main datasets in **Paper [12]**.

**** cloud parameterization and 3D effects on radiation***

1.6 Characterizing cumulus population and properties over Southeast Atlantic

As mentioned above, the representation of cloud processes and interactions with radiation in cumulus regime is challenging, because the cloud field is highly heterogeneous and because cloud size and cover are small. To improve the representativeness of cloud simulations, detailed observations in clouds are crucial for quantifying their variability across scales and for evaluating their physical relationships with aerosols and dynamics. Capitalizing on ENCORE that can account for 3D radiative effects in the retrieval, **Paper [13]** has constructed more than 700 three-dimensional cloud fields at high spatial resolution from the Layered Atlantic Smoke Interactions with Clouds (LASIC) campaign at Ascension Island during July–September 2017 (see an example in **Figure 3**). Among them, ~300 fields are classified as non-precipitating cumulus clouds.

We focus on statistics of cumulus populations and microphysical properties. In particular, information on cloud size distribution is crucial for representing water mass transfer in cumulus schemes in models. While cloud size distributions have previously been estimated by other means (e.g., satellite images and large eddy simulation output), this is the first time we quantify cloud size distributions directly through 3D observational fields. Similar to other studies, we found that the cloud size distribution from LASIC follows a power-law function (**Figure 4**), but we do not see a clear scale break as shown in 2D satellite

images and model output. The slope of the observed power-law function is approximately 1.82, broadly consistent to the range between 1.7 and 2.9 found in the literature; however, a value less than 2 has an important implication. A slope of 2 means that clouds at all sizes contribute equally to the total cloud fraction, while a slope smaller than 2 indicates that larger clouds have larger contributions to cloud fraction (and vice versa).

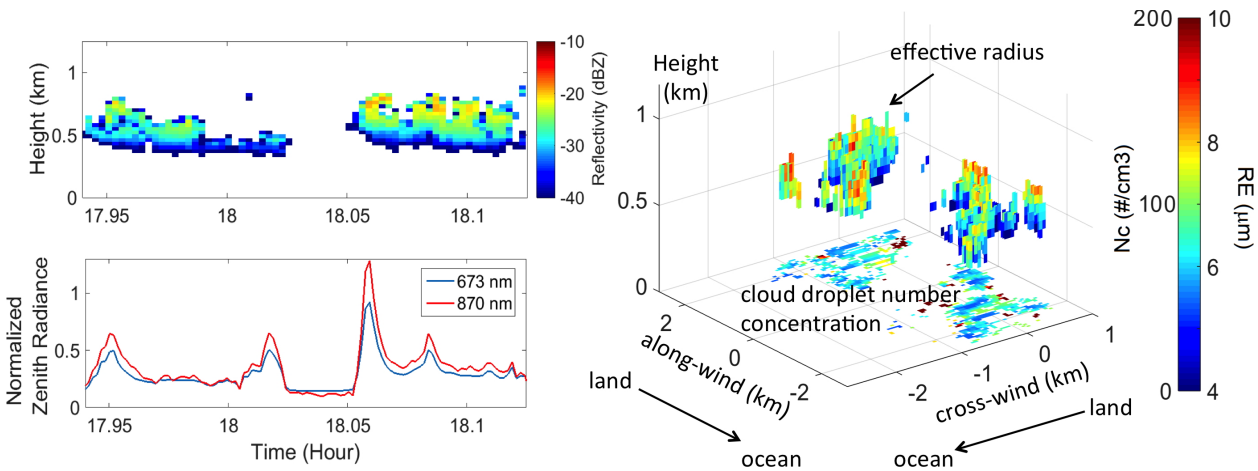

Figure 3. An example showing (left) measurements from zenith-pointing Ka-radar (upper) and a two-channel narrow-field-of-view radiometer (bottom), and (right) 3D retrieved cloud effective radius and 2D cloud droplet number concentration from scanning cloud radar observations.

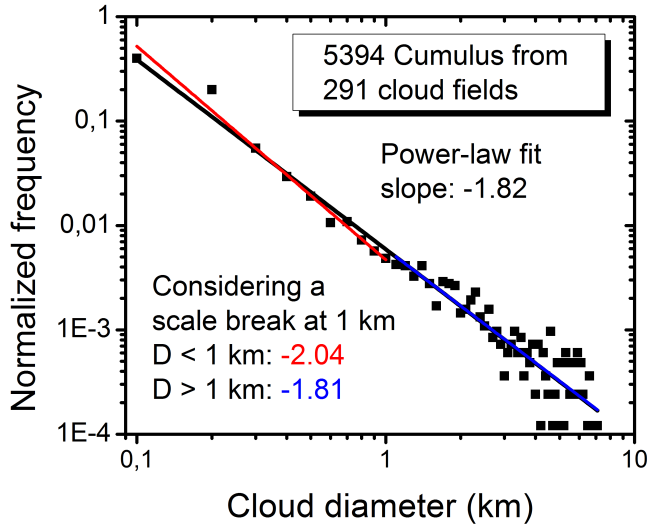

Figure 4. Cloud size distribution derived from 291 cumulus clouds during the LASIC campaign.

Additionally, the microphysical properties from the rich dataset allow us to address a number of questions. Specifically, we assess the impacts of 1D sampling (i.e., soda-straw observation strategy) and 1D retrieval (i.e., neglecting 3D effects during the retrieval) on cloud property statistics and surface radiation, through the following two experiments. Both experiments use our 3D-ENCORE cloud retrieval as a reference for comparisons. In experiment 1, for each reconstructed field, we use *measurements* from 1D, along-wind transects passing over the site to perform 1D cloud retrieval. The difference in cloud properties between Experiment 1 and the reference retrieval is then due to the use of both 1D

sampling and 1D retrieval. In Experiment 2, we use the reference *retrieval* from 1D transects. Since the retrieval is directly taken from the retrieved 3D field, the difference between Experiment 2 and the reference is then only due to 1D sampling.

Table 1 summarizes the statistics from the reference retrieval and two experiments, highlighting a number of key points. Firstly, if cloud properties are accurately retrieved, the 1D sampling does not have a strong impact on statistics of cloud optical and microphysical properties (less than 5% difference), but can largely bias cloud fraction statistics, leading to significant errors in surface radiation. However, this finding should be interpreted with care. The AMF site for the LASIC campaign was located inland, close to the coast but elevated. As a result, cloud fraction over the site tends to be larger than that over oceans due to orography. Therefore, the bias in cloud fraction is likely the consequence of site location and local climatology, and should not be extended for all sites and all cloud types. Secondly, we found that neglecting 3D radiative effects in the retrieval process leads to, on average, underestimated effective radius, and overestimated cloud optical depth and droplet number concentration. Interestingly, these errors behave differently from the findings in satellite retrieval, which reported a substantial overestimation in cloud effective radius, somewhat underestimation in cloud optical depth, and then overall, overestimation in liquid water path due to 3D cloud effects. Finally, due to the bias in cloud fraction as shown in **Table 1**, 1D sampling leads to a substantial underestimation in downwelling surface irradiance at 870 nm by 59–66%, presenting difficulty in reproducing accurate surface radiation.

1.7 Representing 3D cloud effects in a fast radiative transfer code

Current weather and climate models neglect 3D radiative transfer due to its high computational cost. **Papers [5]** and **[6]** present a fast scheme that incorporates 3D effects in broadband radiation calculations, focusing on the longwave spectral region. Surprisingly, we have found that the 3D effects in the longwave are not negligible, as widely believed. This suggests that we can no longer ignore the need for improving our understanding of 3D aspects of both radiation and cloud structures. 3D cloud structures retrieved from the AMF Azores deployment were used to estimate cloud edge length of clouds, required for the fast scheme..

Table 1. Statistics on cloud properties and downwelling irradiance at surface from various setups. Errors for the experiments (the bottom two rows) are indicated in parentheses calculated using the first row as the reference.

Observation & Retrieval Strategy	Cloud fraction	Cloud optical depth	Cloud effective radius (μm)	Cloud droplet # concentration (cm^{-3})	Downwelling surface irradiance at 870 nm ($W\ m^{-2}$)
3D sampling, 3D ENCORE	0.3 ± 0.2	5.5 ± 8.4	6.2 ± 1.7	149 ± 135	0.41 ± 0.24
1D sampling, 3D ENCORE	0.5 ± 0.3 (+68%)	5.4 ± 1.4 (–2%)	5.9 ± 1.4 (–5%)	146 ± 122 (–2%)	0.17 ± 0.16 (–59%)
1D sampling, 1D ENCORE	0.5 ± 0.3 (+68%)	6.4 ± 9.3 (+16%)	5.7 ± 1.4 (–8%)	171 ± 169 (+14%)	0.14 ± 0.12 (–66%)

*** Studying cloud feedback mechanisms**

1.8 Diagnosing cloud feedback processes using ARM observations over SGP, NSA and ENA

Paper [12] uses ARM long-term measurements at SGP, NSA and the AMF Azores deployment to quantify the sensitivity of optical depth of warm clouds to temperature, and to test a number of hypothesized mechanisms of optical depth feedback. These mechanisms include processes through moist-adiabatic lapse rate, cloud phase partitioning, drying efficiency of cloud top mixing, cloud-top inversion strength, and boundary layer decoupling. At temperature below 0°C, the mechanism through moist-adiabatic lapse rate can explain 30–50% of the increase in liquid water path with temperature; ARM observations also support the mechanism through cloud phase partitioning. At temperature above 0°C, it is found that mechanisms of moist-adiabatic lapse rate, cloud-top inversion strength and boundary layer all play a role in decreasing liquid water path with temperature, but evidence supporting the drying efficiency mechanism is not found.

*** 1D cloud and precipitation retrieval for mixed-phase clouds**

1.9 Observing rimed ice from vertically-pointing Doppler radars

Knowledge of the composition of ice particles is crucial for estimating ice water content and snow rates from remote sensing observations. The properties of ice particles are especially uncertain in and below mixed-phase clouds, which are ubiquitous in the extratropics and poles. Using measurements of Ka- and W-band zenith-pointing Doppler radars from the snow experiment (SNEX) of the BAECC field campaign, **Paper [11]** retrieves the density of rimed ice particles; see **Figure 5** for an example. In a case study including low-density aggregates and compact graupel, we found that retrieved snow rates, particle size distribution parameters and ensemble mean ice density compared well with in-situ particle imaging observations at the surface.

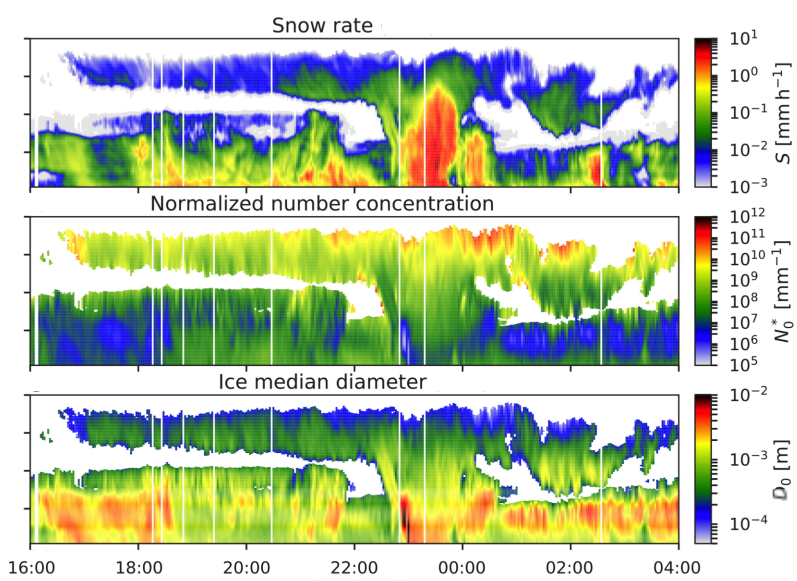

Figure 5. The retrieved snow rate (top), normalized number concentration (middle), and median particle diameter (bottom) from dual-frequency reflectivity and Ka-band Doppler velocity, for the 21 February 2014 case.

2. Research outputs

2.1 Publication

[1] **Fielding, M. D., J. C. Chiu, R. J. Hogan** and G. Feingold, 2014: A novel ensemble method for retrieving properties of warm cloud in 3-D using ground-based scanning radar and zenith radiances, J. Geophys. Res. Atmos., 119, doi:10.1002/2014JD021742.

[2] **Chiu, J. C**., J. A. Holmes, **R. J. Hogan**, and E. J. O'Connor, 2014: The interdependence of continental warm cloud properties derived from unexploited solar background signals in ground-based lidar measurements, Atmos. Chem. Phys., 14, 8389-8401, doi:10.5194/acp-14-8389-2014.

[3] **Fielding, M. D., J. C. Chiu, R. J. Hogan**, G. Feingold, E. Eloranta, E. J. O'Connor and M. P. Cadeddu, 2015: Joint retrievals of cloud and drizzle in marine boundary layer clouds using ground-based radar, lidar and zenith radiances, Atmos. Meas. Tech., 8, 2663–2683, doi:10.5194/amt-8-2663-2015.

[4] Wood, R., M. Wyant, C. S. Bretherton, J. Rémillard, P. Kollias, J. Fletcher, J. Stemmler, S. deSzoeke, S. Yuter, M. Miller, D. Mechem, G. Tselioudis, **J. C. Chiu**, J. Mann, E. O'Connor, R. Hogan, X. Dong, M. Miller, V. Ghate, A. Jefferson, Q. Min, P. Minnis, R. Palinkonda, B. Albrecht, W. Wiscombe, E. Luke, C. Hannay, and Y. Lin, 2015: Clouds, Aerosol, and Precipitation in the Marine Boundary Layer: An ARM Mobile Facility Deployment, Bull. Amer. Meteor. Soc., 96, 419–440.

[5] Schafer, S. A. K., **R. J. Hogan**, C. Klinger, **J. C. Chiu** and B. Mayer, 2016: Representing 3D cloud–radiation effects in two-stream schemes: 1. Longwave considerations and effective cloud edge length, *J. Geophys. Res. Atmos*., 10.1002/2016JD024876.

[6] **Hogan, R. J.**, S. A. K. Schafer, C. Klinger, **J. C. Chiu** and B. Mayer, 2016: Representing 3D cloud-radiation effects in two-stream schemes: 2. Matrix formulation and broadband evaluation, *J. Geophys. Res. Atmos*., 10.1002/2016JD024875.

[7] Yang, W., A. Marshak, P. J. McBride, **J. C. Chiu**, Y. Knyazikhin, K. S. Schmidt, C. Flynn and E. R. Lewis, 2016: Observation of the spectral-invariant properties of clouds in cloudy-to-clear transition zones during MAGIC, *Atmos. Res.,* doi:10.1016/j.atmosres.2016.08.004.

[8] D. Painemal, **J. C. Chiu**, P. Minnis, C. Yost, X. Zhou, M. Cadeddu, E. Eloranta, E. R. Lewis, R. Ferrare, and P. Kollias, 2017: Aerosol and cloud microphysics co-variability in the northeast Pacific boundary layer estimated with ship-based and satellite remote sensing observations, *J. Geophys. Res. Atmos*., doi:10.1002/2016JD025771. .

[9] Mason, S. L., **J. C. Chiu**, **R. J. Hogan**, and L. Tian, 2017: Improved rain-rate and drop-size retrievals from airborne and spaceborne Doppler radar, *Atmos. Chem. Phys*., 17, 11567-11589.

[10] Grosvenor, D. P. et al. (including **J. C. Chiu**), 2018: Remote sensing of droplet number concentration in warm clouds: A review of the current state of knowledge and perspectives, *Reviews of Geophysics*, 56, 409–453.

[11] Mason, S. L., **J. C. Chiu**, R. J. Hogan, D. Moisseev, and S. Kneifei, 2018: Retrievals of riming and snow particle density from vertically-pointing Doppler radars, *J. Geophys. Res. Atmos.,* 123. https://doi.org/10.1029/2018JD028603.

[12] Terai, C. R., Y. Zhang, S. A. Klein, M. D. Zelinka, **J. C. Chiu**, and Q. Min, 2018: Mechanisms behind the low-cloud optical depth response to temperature in ARM site observations, *J. Geophys. Res. Atmos.*, accepted.

[13] **Blanchard, Y., J. C. Chiu**, B. Isom, **R. J. Hogan**, and P. Zuidema, 2018: Characteristics of Cumulus Population and Properties over Southeast Atlantic, *to be submitted to ACP*.

2.2 Talks for presenting ASR-funded research results

Year	Organization/Conference	Presenter
2018	AMS Joint conference on Cloud Physics and Atmospheric Radiation (joint plenary session)	Blanchard
2018	Blog at University of Reading	Blanchard
2018	University of Michigan (invited)	Chiu
2017	AGU	Blanchard
2017	EGU	Chiu
2016	Radiation Science Workshop (invited)	Chiu
2016	Academia Sinica, Taiwan (invited)	Chiu
2016	Conference of High definition clouds and precipitation for advancing climate prediction, Berlin, Germany (invited)	Chiu
2015	Gordon Research Conference in Radiation & Climate, Maine US (invited)	Chiu
2015	IUGCC General Assembly, Prague, Czech Republic	Chiu
2014	AMS Joint conference on Cloud Physics and Atmospheric Radiation	Fielding