Final Report

Study of Shortwave Spectra in Fully 3D Environment: Synergy Between Scanning Radars and Spectral Radiation Measurements

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Project Title:	Study of Shortwave Spectra in Fully 3D Environment: Synergy Between Scanning Radars and Spectral Radiation Measurements
PI Name:	Jui-Yuan Christine Chiu, Associate Professor, 44-118-378-5574, c.j.chiu@reading.ac.uk
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A. Executive Summary

ARM set out 20 years ago to “close” the radiation problem, that is, to improve radiation models to the point where they could routinely predict the observed spectral radiation fluxes knowing the optical properties of the surface and of gases, clouds and aerosols in the atmosphere. Only then could such radiation models form a proper springboard for global climate model (GCM) parameterizations of spectral radiation. Sustained efforts have more or less achieved that goal with regard to longwave radiation; ASR models now routinely predict ARM spectral longwave radiances to 1–2%. Similar efforts in the shortwave have achieved far less; the successes are mainly for carefully selected 1D stratiform cloud cases. Such cases amount, even with the most optimistic interpretation, to no more than 30% of all cases at SGP. The problem has not been lack of effort but lack of appropriate instruments.

The new ARM stimulus-funded instruments, with their new capabilities, will dramatically improve this situation and once again make progress possible on the shortwave problem. The new shortwave spectrometers will provide a reliable, calibrated record including the near infrared – and for other climatic regimes than SGP. The new scanning radars will provide the 3D cloud view, making it possible to tackle fully 3D situations. Thus, our main theme for the project is the understanding and closure of the surface spectral shortwave radiation problem in fully 3D cloud situations by combining the new ARM scanning radars and shortwave spectrometers with the arsenal of radiative transfer tools.

Specifically, the objectives of the project are to:

- Identify the optimal radar scanning strategy for spectral radiation closure;
- Exploit shortwave zenith radiance measurements to supplement radar retrievals; and
- Develop and provide more accurate estimate of cloud retrievals with uncertainty to advance our understanding of cloud-aerosol-precipitation interactions.

We have completed all the objectives stated in the proposal and published 11 peer-review journal papers. A number of research activities are included and summarised in this report.

B. Highlights of Research Output (References to cited papers are given in [])

1. Optimizing cloud radar scan strategy for reconstructing cumulus cloud fields

The new ARM scanning radars provide a unique opportunity to make robust 3D cloud observations. **In [6]**, we explore this new capability and assess the ability of six cloud radar scan strategies to reconstruct cumulus cloud fields. Using snapshots of both clean and polluted cloud fields from large eddy simulations (LES), we have found that the Cross-Wind Range Height Indicator (CWRHI) would be the best scan strategy for minimizing overall bias in liquid water content and surface shortwave irradiance, because it is the most effective at detecting low reflectivity clouds. The frequent return to zenith gives good vertical coverage, allowing detection of high cloud. However, CWRHI works better under high wind speed conditions. For slow wind speed or large solar zenith angle, the Plan Position Indicator (PPI) scan outperforms the other scan strategies and can easily be optimised with information on cloud base and height. These findings provide an important guideline for ARM to reproduce realistic detailed structures of clouds from scanning cloud radar measurements.

Paper [6] has also discovered that radar sensitivity plays an important role in a scan strategy's success. When using a realistic radar sensitivity of −37.5 dBZ at 1 km, large overestimates of 10–26 W m^{-2} μm^{-1} (20–100 % of the CRE) in domain average surface irradiance at 870 nm wavelength are found – particularly in polluted cases where cloud droplets tend to be smaller and easily missed (**Fig. 1**). Drizzle drops are also problematic; if treated as cloud droplets, reconstructions are poor, leading to large underestimates of 25–40 W m^{-2} μm^{-1} (50–75% of the CRE) in domain average surface irradiance. Nevertheless, a synergistic retrieval approach combining the detailed cloud structure obtained from scanning radar with the microphysical cloud information gained from other instruments would potentially make accurate solar radiative transfer calculations in broken cloud possible for the first time.

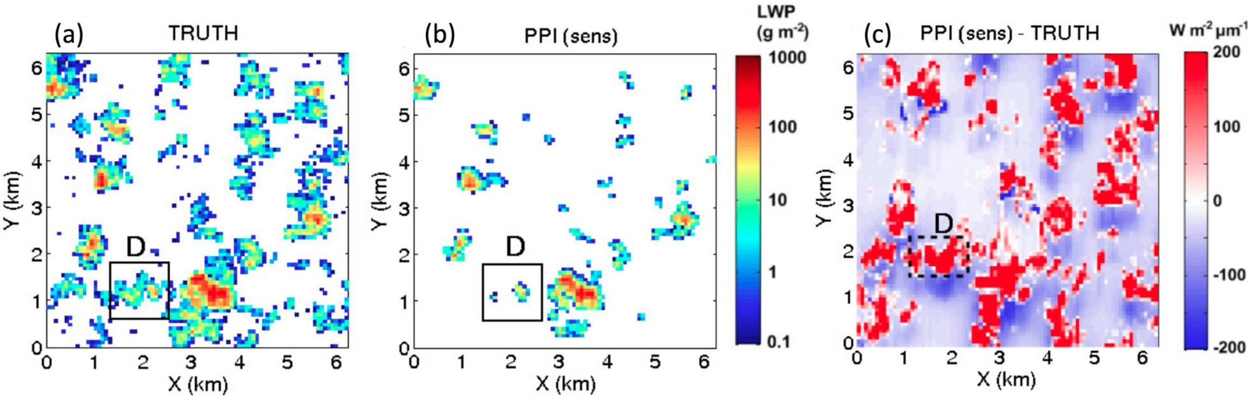

Figure. 1. The truth (a) and reconstructed (b) cloud fields, and the corresponding surface downwelling irradiance difference between two (c), assuming realistic radar sensitivity. Label D highlights that clouds are missed because of small cloud droplet size, leading a positive irradiance difference.

2. 3D ENCORE – cloud retrievals developed for ARM scanning cloud radar measurements

To take full advantage of the ARM new scanning radar measurements, **Paper [2]** 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. ENCORE has a number of novelties and key features:

- It exploits synergetic measurements to retrieve the full 3D distribution of cloud properties that are consistent between shortwave and microwave spectral regions, using ARM scanning cloud radar and shortwave spectral radiometers.
- It exploits an iterative Ensemble Kalman Filter approach to build the retrieval method under a fully 3D framework, which is extremely difficult for other retrieval techniques.
- It fully accounts for 3D radiative effects in our method and thus retrievals.
- It can be easily switched between 1D and 3D versions, depending on the availability of scanning cloud radar.
- It can include microwave radiometer (MWR) in the retrieval, or exclude MWR and therefore retain this valuable instrument as an independent validation source.

Using ARM Mobile Facility measurements at the Azores in 2009, we show 3D cloud retrievals for overcast stratocumulus and challenging shallow cumulus in **Fig. 2**. For the stratocumulus case, ENCORE shows good agreement with independent retrievals of liquid water path from the two-channel microwave radiometers with an error of 20 g m^{-2}, which is comparable to retrieval uncertainty. Similar intercomparison was not performed for the shallow cumulus case, because microwave radiometers had 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.

In short, these new scanning cloud radar observations open the door to many new lines of research and ultimately will help unravel the influence of aerosol on clouds in both a macrophysical and microphysical sense. They will also give insight to the 3D radiative properties of boundary-layer clouds.

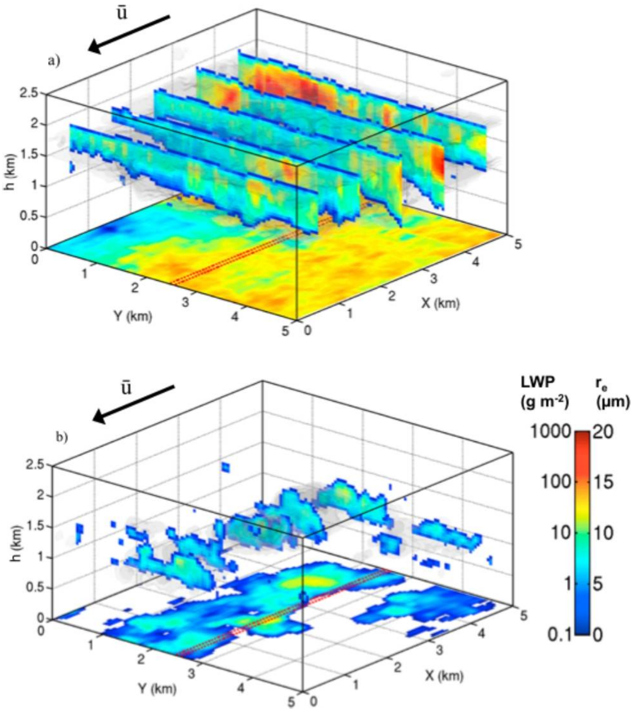

Figure 2. Retrieved cloud fields for (top) stratocumulus case and (bottom) cumulus case, with 3-D liquid water content plotted as grey isosurfaces, slices of 3-D effective radius (r_e) plotted along the Y axis and liquid water path (LWP) plotted at the surface. The mean wind (u) direction is shown by the black arrow, while the track of radiances along Y = 2.5 km is shown by the red dashed line.

3. 1D ENCORE – simultaneous drizzle/cloud properties from MAGIC

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 [1]** developed an adaptation to ENCORE to overcome this hurdle and characterised 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 (as shown in **Fig. 3**). These retrievals are based on a core trio of measurements from radar, lidar and shortwave radiometer.

The retrieval is currently being applied to the entire MAGIC dataset so that the covariance between vertically resolved cloud and drizzle variables can be explored. Potential other applications of 1D ENCORE are diverse, including investigations into precipitation initiation, aerosol effects on drizzle suppression and the role of precipitation in cloud field organisation and variability. Further, these retrievals are suited to help parameterise sub-grid variability of cloud and drizzle in general circulation models and cloud parameterisations based on probability density functions. Crucially, this adaption to ENCORE will lead to the development of a full 3D cloud retrieval that is not restricted to non-precipitating cloud.

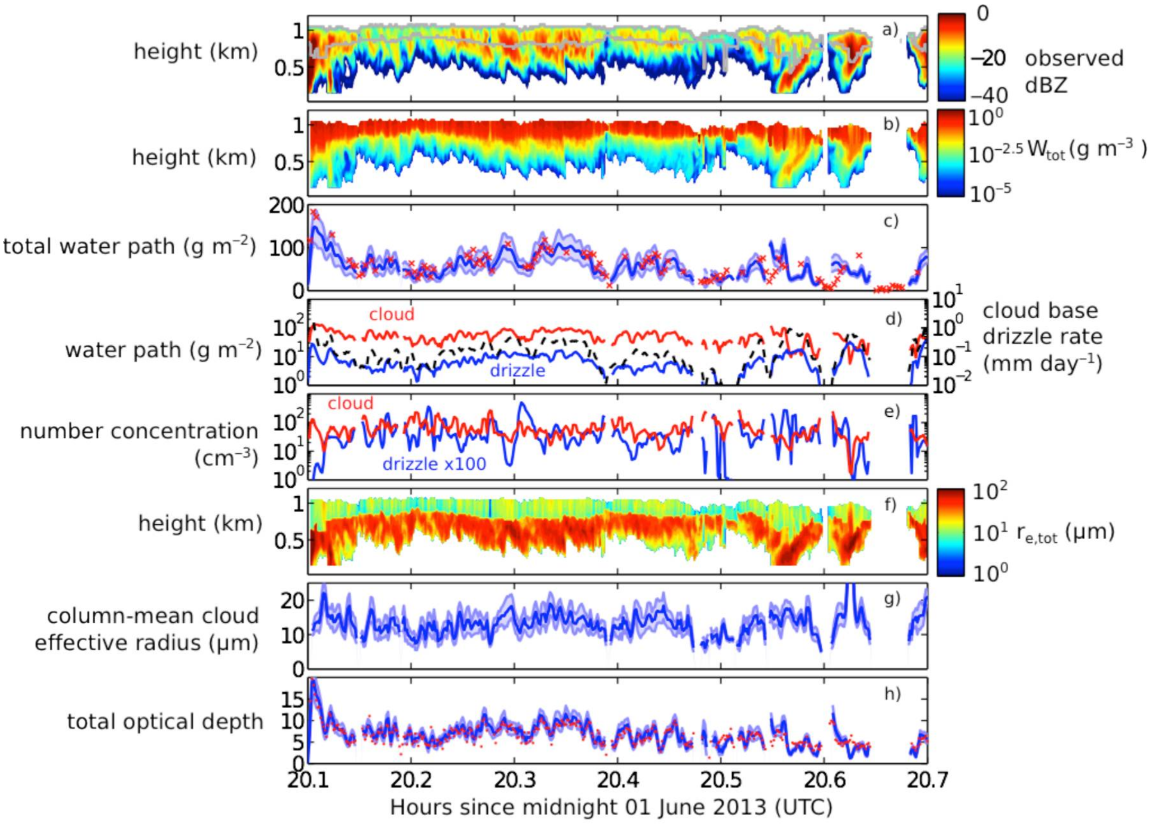

Figure 3. Retrieved cloud properties on 01 June 2013 during MAGIC in predominantly drizzling conditions. Panels show time series of a) observed KAZR radar reflectivity factor, b) retrieved total water content, c) retrieved total water path from ENCORE (blue line) and the microwave radiometer (red crosses), d) retrieved cloud (red) and drizzle (blue) liquid water path and cloud base drizzle rate (black dashed line), e) retrieved cloud droplet number concentration (red) and retrieved drizzle droplet number concentration multiplied by 100 (blue), f) retrieved total effective radius, g) retrieved column-averaged cloud effective radius and h) cloud optical depth (blue line) and radiance only retrieval (red dots). The blue shading represents one standard deviation uncertainty in the retrieval.

4. Assessing aerosol impacts on drizzle intensity and frequency from AMF data

Aerosols have a strong effect on climate via their potential to modify the properties of warm clouds; an increase in aerosol loading could reduce drizzle production, modulate the stability of the boundary layer, and change cloud properties, lifetime and extent, which is referred to as the second aerosol indirect effect. Recent studies showed that global models significantly overestimate drizzle, which calls into question the fidelity with which the second indirect effect of aerosol is captured. In **Paper [5]**, we analyzed high-temporal resolution observations from the Atmospheric Radiation Measurement (ARM) Mobile Facility (AMF) deployments in the Black Forest, Germany during April–Dec. 2007 and at the Azores from June 2009 to Dec. 2010. Three key findings are reported as follows.

First, using collocated Aerosol Observing Systems, active and passive remote sensing instruments, **Fig. 4** shows that cloud-base drizzle intensity (R_{cb}) statistically significantly increases with liquid water path (LWP) and decreases with cloud condensation nuclei number concentration (N_{CCN}), which is consistent with the hypothesis that greater N_{CCN} redistributes cloud water to more numerous and smaller droplets, reducing the collision-coalescence rates and further decreasing drizzle rate. The quantitative relationship derived from the ARM data, showing that R_{cb} is proportional to LWP with an exponent of 1.68±0.05 and N_{CCN} with an exponent of (-0.66±0.08), is valuable for further constraining precipitation rate in models.

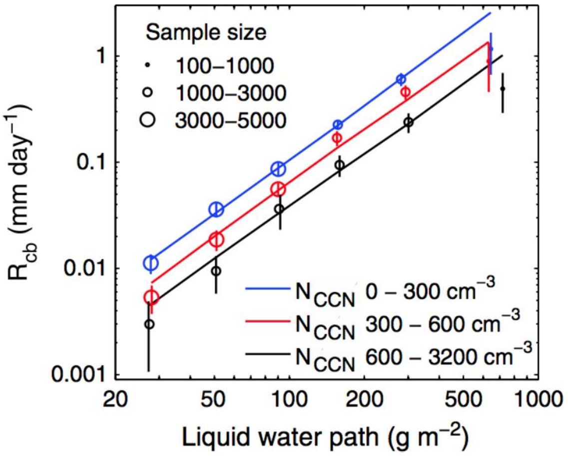

Figure 4. Cloud-base drizzle rate as a function of liquid water path for various number concentrations of cloud condensation nuclei (CCN). Error bars represent a 95% confidence interval accounting for sample dependence. The size of symbols illustrates the sample size *N*.

Second, the precipitation susceptibility to N_{CCN} ranges between 0.5 and 0.9 and generally decreases with LWP. Although this feature agrees well with large-eddy simulations of shallow cumulus particularly for LWP between 100 and 300 g m^{-2}, there is still a large degree of uncertainty in our precipitation susceptibility, which can be reduced by including more observations. Additionally, analysis and intercomparisons of precipitation susceptibility to other aerosol proxies, such as cloud droplet number concentration, aerosol optical depth, and aerosol index could help resolve outstanding discrepancies among various studies.

Finally, for the first time, **Paper [5]** reported, the susceptibility of the probability of precipitation to N_{CCN} (S_{POP}) from ground-based measurements (**Fig. 5**), and highlighted the difference in S_{POP} between observations from ground-based, aircraft and satellites, and simulations. S_{POP} from AMF data is higher than that from satellites, and equivalent with aircraft observations and high-resolution simulations. This indicates that the high-resolution multi-scale climate model may have already had the ability to represent aerosol-cloud-precipitation interactions properly, and may not overestimate the response of LWP to aerosol perturbation as previously thought. More experiments such as intercomparison between high-resolution ground-based measurements and simulations over fixed sites for a longer time period will provide further confirmation.

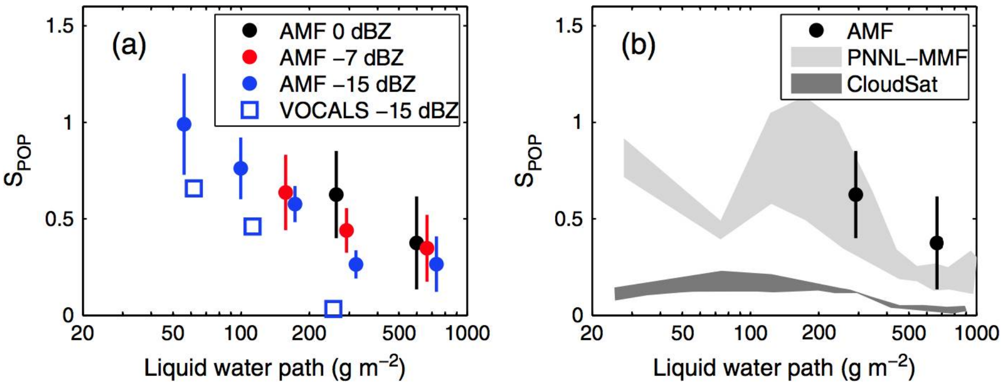

Figure 5. (a) Susceptibility of probability of precipitation (S_{POP}) derived from AMF measurements using reflectivity thresholds of 0, 7 and 15 dBZ, compared with S_{POP} for the 15 dBZ threshold from the VOCALS-REx field campaign [*Terai et al.*, 2012, Figure 3]. (b) S_{POP} based on the 0 dBZ threshold from AMF compared to S_{POP} for different atmospheric stability regimes from CloudSat observations and the PNNL-MMF outputs at 4 km [*Wang et al.*, 2012].

5. Retrieving effective droplet size from ARM sunphotometer measurements

Cloud droplet effective radius is one of the most fundamental cloud properties for understanding cloud formation, dissipation and interactions with aerosol and drizzle. While tremendous efforts have been made in providing routine cloud droplet effective radii from satellite measurements, ground-based retrievals are limited and the discrepancies among different retrievals remain unresolved. **In [8]**, we have developed a new retrieval method for cloud effective droplet size and conducted extensive tests for non-precipitating liquid water clouds. The method uses zenith radiances at visible and near-infrared wavelengths from ARM and Aerosol Robotic Network (AERONET) cloud mode observations. The underlying principle is to combine a liquid-water-absorbing wavelength (i.e., 1640 nm) with a non-water-absorbing wavelength for acquiring information on cloud droplet size and optical depth.

For actual observations with a liquid water path less than 450 g m^{-2} at the ARM Oklahoma site during 2007–2008, our 1.5-min-averaged retrievals are generally larger by around 1 µm than those from combined ground-based cloud radar and microwave radiometer at a 5-min temporal resolution. We also compared our retrievals to those from combined shortwave flux and microwave observations for relatively homogeneous clouds (see an example in **Fig. 6**), showing that the bias between these two retrieval sets is negligible, but the root-mean-squared error of 2.6 µm and the relative deviation of 22% are larger than those found in our simulation case. Finally, our cloud effective droplet radii agree to better than 11% with satellite observations and have a negative bias of 1 µm. Overall, our retrieval method provides reasonable cloud effective radius estimates, which not only enhance the cloud products of both ARM and AERONET, but also provide valuable information for the ARM Cloud-Aerosol-Precipitation Interaction and Cloud Lifecycle Working groups.

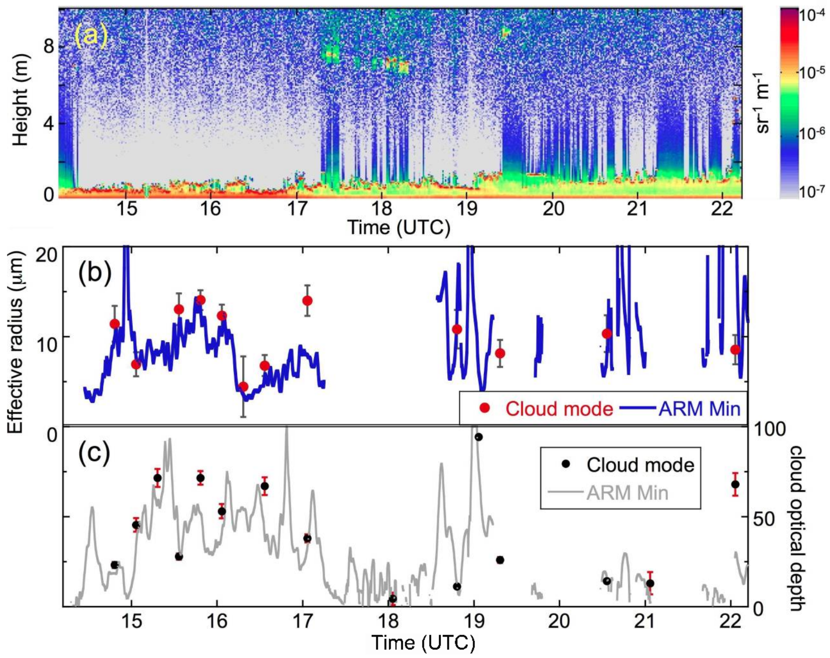

Figure 6. (**a**) Attenuated backscatter signal from micropulse lidar on 15th June 2007. A time series of effective radius (**b**) and cloud optical depth (**c**) from cloud-mode data and the ARM Min dataset. The error bars represent one standard deviation. In (b), we omit the default values of 8 µm reported in the ARM Min retrievals. In (c), cloud optical depth from the ARM Min dataset was truncated at 100 for plotting purposes.

6. Continental warm cloud properties derived from 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 properly, **Paper [3]** introduced a novel retrieval method that exploits the solar background signals previously treated as noises and removed in lidar measurements. Combining these new optical depth retrievals with radar and microwave observations at the ARM Oklahoma site during 2005–2007, **Fig. 7** shows 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.

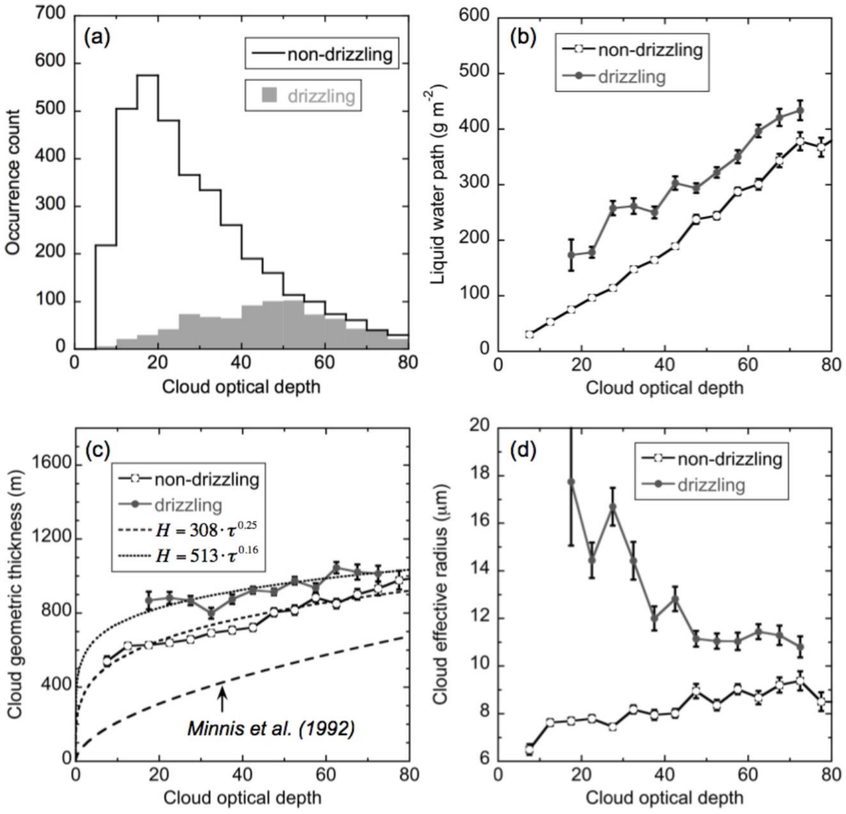

Figure 7. (**a**) Occurrence histogram of cloud optical depth (τ); plots of (**b**) liquid water path, (**c**) geometric thickness (H in meters) of cloud layer and (**d**) cloud effective radius versus optical depth for low-level stratiform clouds, using 1 min averaged retrievals at the ARM Oklahoma site during the period 2005–2007. A cloud-base radar reflectivity threshold of −15 dBZ is used for drizzle classification; a cloud is drizzling if its cloud-base reflectivity exceeds the threshold, otherwise, non-drizzling. Error bars represent 1 standard error. Three power-law relationships are co-plotted in (**c**); dotted lines are based on ARM data, while the dashed line is adapted from the satellite-based finding reported in *Minnis et al.* (1992). (**b–d**) omit bins of cloud optical depth with a sample size smaller than 25.

One of the important applications of the new method is to the existing lidar networks, including the high-density ceilometer networks in the United Kingdom, France and Germany that have been established for monitoring volcanic plumes. Combined with the ability of lidars to resolve vertical distributions of aerosol properties below cloud layers, collocated and simultaneous measurements of aerosol and cloud are possible, which can help advance our understanding of aerosol–cloud interactions.

7. Investigating cloud optical and microphysical properties during the AMF deployment in China

In collaboration with the ARM Science team members at the University of Maryland, we retrieved cloud optical and microphysical properties using shortwave fluxes and hyperspectral radiances collected during the AMF China campaign to evaluate satellite retrievals in **Paper [7]**. Additionally, seasonal variation of cloud properties and differences between raining and non-raining clouds are also examined. In general, we have found that raining and non-raining clouds have significant differences in liquid water path (LWP), cloud optical depth and effective radius. Rainfall frequency is best correlated with LWP, and least with effective radius. We have also found that on average, relative to surface-based retrievals, the mean differences of satellite retrievals in

LWP, optical depth and effective radius are about 22–26%, 10–34% and 12–30%, respectively. These discrepancies indicate that satellite cloud products still suffer from non-negligible uncertainties over the Yangtze Delta region.

8. Understanding spectral-invariant behaviour of zenith radiance around cloud edge – implications in aerosol/cloud remote sensing

To the naked eye, clouds appear to have sharp boundaries. But cloud boundaries are actually somewhat fuzzy. Fuzzy cloud boundaries create major headaches for studies of aerosol indirect effect and aerosol radiative forcing. Previous studies, funded by ASR, discovered a spectral-invariant behaviour of zenith radiance, which is mostly sensitive to cloud properties and has little sensitivity to other factors. While this suggests that the spectrally invariant relationship can be used to infer cloud properties near cloud edges even with insufficient or no knowledge about surface albedo and aerosol properties, a theoretical explanation is lacking to understand where the spectral invariance comes from. **Paper [10]** shows, numerically and theoretically, that the spectrum of single scatter albedo of water droplets at a given effect radius and at weakly absorbing wavelengths can be well approximated by on known spectrum of water droplets at another effective radius, which helps to interpret the spectra-invariant behaviour in zenith radiance measurements. Interestingly, this finding is valid not only for water droplets, but also for non-spherical ice crystals.

C. Research Output – Publications

(Members of our science team are in bold)

[1] **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.

[2] **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.

[3] **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.

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[5] Mann, J. A. L., **J. C. Chiu**, **R. J. Hogan**, E. J. O'Connor, T. S. L'Ecuyer, T. H. M. Stein, and A. Jefferson, 2014: Aerosol impacts on drizzle properties in warm clouds from ARM Mobile Facility maritime and continental deployments, *J. Geophys. Res. Atmos.*, 119, doi:10.1002/2013JD021339.

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[7] Liu, J., Z. Li, Y. Zheng, **J. C. Chiu**, F. Zhao, C. Li, M Cadeddu and M. Cribb, 2013: Cloud optical and microphysical properties derived from ground-based and satellite sensors over a site in the Yangtze Delta Region, *J. Geophys. Res.* (Special Issue on EAST-AIRC), 118, 9141–9152, doi:10.1002/jgrd.50648.

[8] **Chiu, J. C.**, A. Marshak, C.-H. Huang, T. Varnai, **R. Hogan**, D. M. Giles, B. N. Holben, E. O'Connor, Y. Knyazikhin, W. J. Wiscombe, 2012: Cloud droplet size and liquid water path retrievals from zenith radiance measurements: examples from the Atmospheric Radiation Measurement Program and the Aerosol Robotic Network. *Atmos. Chem. Phys.*, 12, 10313–10329.

[9] Anton, M., L. Alados-Arboledas, J. L. Guerrero-Rascado, M. J. Costa, **J. C. Chiu**, and F. J. Olmo, 2012: Experimental and modeled UV erthemal irradiance under overcast conditions: The role of cloud optical depth. *Atmos. Chem. Phys.*, 12, 11723–11732.

[10] Marshak, A., Y. Knyazikhin, **J. C. Chiu**, and W. J. Wiscombe, 2012: On spectral invariance of single scattering albedo for water droplets and ice crystals at weakly absorbing wavelengths. *J. Quant. Spectrosc. Radiat. Transfer*, doi:10.1016/j.jqsrt.2012.02.021.

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