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DOE/SC-ARM-15-029

MAGIC Cloud Properties from Zenith Radiance Data Final Campaign Summary

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January 2016

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Final Campaign Summary

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Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Executive Summary

Cloud droplet size and optical depth are the most fundamental properties for understanding cloud formation, dissipation and interactions with aerosol and drizzle. They are also a crucial determinant of Earth's radiative and water-energy balances. However, these properties are poorly predicted in climate models. As a result, the response of clouds to climate change is one of the major sources of uncertainty in climate prediction.

To understand the feedback processes of marine boundary layer clouds using the Atmospheric Radiation Measurement (ARM) Climate Research Facility's second Mobile Facility (AMF2), the Marine ARM GPCI[1] Investigation of Clouds (MAGIC) field campaign aimed to observe the transition from the stratocumulus to shallow trade-wind cumulus. These clouds pose great challenges for remote sensing techniques because of their highly inhomogeneous and fast-evolving nature. This campaign provided observations of cloud optical depth and effective droplet size at high temporal resolution using the ARM sunphotometer, which has a proper narrow field of view for observing broken clouds and the necessary narrow wavelength bands. The cloud properties were retrieved from a physics-based method and complemented retrievals from flux, microwave and active sensors.

The campaign has successfully operated the ARM Cimel Sunphotometer in cloud mode and provided zenith radiance measurements continuously during daytime for May through July 2013. The mean cloud optical depth and cloud effective radius are 13 and 10 μm over the three months, generally consistent with satellite observations and some in-situ measurements for marine boundary layer clouds. These zenith radiance observations also provide an excellent opportunity to maximize synergy with the most advanced radar and lidar measurements for simultaneous cloud and drizzle properties. More importantly, this campaign has demonstrated that a sunphotometer marine deployment can provide robust cloud mode observations and will be invaluable for many future deployments.

[1] GPCI = GCSS Pacific Cross-section Intercomparison, a working group of GCSS
GCSS = GEWEX Cloud Systems Study
GEWEX = Global Energy and Water Cycle Experiment, a core project of the World Climate Research Programme.

Acronyms and Abbreviations

ARM	Atmospheric Measurement Radiation
CSPHOT	Cimel Sunphotometer
DISORT	Discrete-ordinate-method Radiative Transfer Model
ENCORE	ENsemble ClOud REtrieval
EPROM	erasable programmable read-only memory
FOV	field of view
GCSS	GEWEX Cloud Systems Study
GEWEX	Global Energy and Water Cycle Experiment, a core project of the World Climate Research Programme
GPCI	GCSS Pacific Cross-section Intercomparison, a working group of GCSS
HSRL	High Spectral Resolution Lidar
KAZR	Ka-band ARM Zenith Radar
MAGIC	Marine ARM GPCI Investigations of Clouds
PI	principal investigator
SSFR	Solar Spectral Flux Radiometer
SHDOM	Spherical Harmonic Discrete Ordinate Method
SAS-Ze	Shortwave Spectrometer

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1.0 Background

This campaign provided routine cloud observations at high temporal resolution, using the Atmospheric Radiation Measurement (ARM) Climate Facility's Cimel Sunphotometer (CSPHOT). The CSPHOT is a sun/sky radiometer with a 1.2° field of view (FOV) that measures radiance at six wavelengths: 440, 500, 675, 870, 1020 and 1640 nm. The CSPHOT was originally designed for monitoring aerosol properties, using direct sun measurements for aerosol optical depth and sky radiances for aerosol microphysical and optical properties. Since these aerosol-related measurements require a capability of accurate pointing, robotic automatic mode has not been deployed for maritime purposes due to ship movements. This field campaign proposed to operate CSPHOT continuously in a "cloud-mode" during the Marine ARM GPCI[1] Investigations of Clouds (MAGIC) campaign, capitalizing on the fact that when clouds block the sun, direct sun and sky measurements are not appropriate for retrieving aerosol properties. In cloud mode, CSPHOT points directly up (i.e., zenith) and collects radiance measurements every 10 second, which can be used to retrieve cloud properties for both overcast and broken cloud situations (Chiu et al. 2010; 2012) and can help observe the transition from stratocumulus to cumulus cloud regimes during MAGIC.

To operate CSPHOT in a continuous cloud mode, the instrument's erasable programmable read-only memory (EPROM) was re-programmed by Cimel. The delivery of the re-programmed CSPHOT was delayed; the instrument was then tested in the Brookhaven National Laboratory and shipped to Los Angeles for deployment in December 2012. Unfortunately, due to a revised shipping schedule, CSPHOT did not start its measurements until May 2013. In summary, CSPHOT cloud-mode observations are available for MAGIC Lag 10–15 during May–July 2013. This time period overlapped with observational periods of other advanced "guest" instruments such as High Spectral Resolution Lidar (HSRL) Solar Spectral Flux Radiometer (SSFR), allowing us to explore research opportunities in drizzle retrieval and cloud-aerosol interactions. Information on these MAGIC transacts is listed in Table 1.

Table 1. Information on cruise departure and arrival time (in UTC) for MAGIC transacts between Los Angles (LA) and Hawaii (HI) when CSPHOT cloud-mode observations are available.

	A		B	
Leg Index	Depart LA	Arrive HI	Depart HI	Arrive LA
10	2013-05-11, 12:10	2013-05-16, 06:00	2013-05-17, 16:35	2013-05-23, 13:15
11	2013-05-25, 11:30	2013-05-30, 06:30	2013-05-31, 11:20	2013-06-06, 13:25
12	2013-06-08, 11:25	2013-06-13, 06:20	2013-06-14, 16:40	2013-06-20, 13:30
13	2013-06-22, 11:30	2013-06-27, 07:40	2013-06-28, 17:35	2013-07-03, 23:00
14	2013-07-07, 17:35	2013-07-12, 06:30	2013-07-13, 11:30	2013-07-18, 23:10
15	2013-07-20, 12:00	2013-07-25, 05:40	2013-07-26, 13:15	2013-08-01, 13:30

[1] GPCI = GCSS Pacific Cross-section Intercomparison, a working group of GCSS
GCSS = GEWEX Cloud Systems Study
GEWEX = Global Energy and Water Cycle Experiment, a core project of the World Climate Research Programme.

2.0 Methodology

We use the method proposed in Chiu et al. (2012) to retrieve cloud optical depth and effective radius simultaneously. The method uses zenith radiance measurements at 440, 870 and 1640 nm, with the underlying principle that cloud optical depth is mainly determined by non-water–absorbing wavelength (e.g., 440 and 870 nm) and effective radius by liquid-water–absorbing wavelength (e.g., 1640 nm). In our retrieval method, we assumed 5 % uncertainty in zenith radiance measurements and 10% uncertainty in surface albedo at all wavelengths. These normally distributed uncertainties are used to perturb the observed zenith radiance and surface albedo estimate. We then compare the perturbed zenith radiance to calculated lookup tables and search for possible solutions. The lookup tables were computed from the discrete-ordinate-method radiative transfer model (DISORT; Stamnes et al. 1988) over reasonable ranges of cloud optical depth (up to 100), effective cloud fraction, and effective cloud radius ranging from 4 to 20 μm at various solar zenith angles. Additionally, for each cloud-mode measurement, we repeat the same retrieval procedure 40 times; the final retrievals for cloud optical depth and effective radius are given as the mean of these 40 repetitions with an uncertainty estimated by the standard error. In general, the uncertainty in retrieved cloud optical depth and effective radius is about 15% for stratocumulus clouds with liquid water paths less than 300 g m^{-2} over vegetated surfaces.

Since these routine cloud-mode observations were collected over the ocean rather than over land, a number of modifications were needed in the retrieval method to account for ocean surface albedo and ship movements. First, we calculate ocean albedo by subroutines used in SHDOM (Evans, 1998). Second, the CSPHOT was not mounted on a stabilized platform, and thus it frequently pointed slightly off the zenith due to ship movements. Using information on ship pitch, roll and yaw measurements (stored in navigation data files available in the ARM Data Archive), we calculated the actual pointing angle of CSPHOT and defined the departure from the zenith as the “beam angle.” Note that the beam angle is essentially the zenith angle of the CSPHOT pointing direction.

The beam angle β is given by:

$$\beta = \cos^{-1}(\cos\alpha \cos\varphi), \quad (1)$$

where α is the ship pitch angle and φ is the roll angle. During the campaign in May–July 2013, Figure 1 shows that 75% of the beam angles are within 1° and 96% are within 2°. For optically thick clouds, such small departure angles have very little impact on retrieved cloud properties, but they are not completely negligible for optically thin clouds. Overall, this small range of the departure angles is promising and suggests that automatic routine cloud mode observations can easily be corrected and reliable without a stabilized platform.

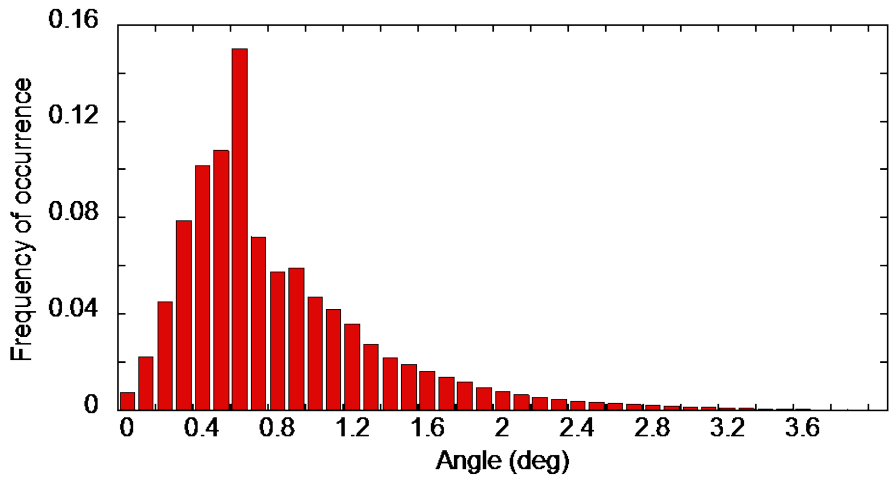

Figure 1. Histograms of beam angles of CSPHOT pointing directions during Leg 10–Leg 15 of the MAGIC field campaign

By defining that the zenith and azimuth angles for the CSPHOT and the sun are respectively (β, ϕ) and (θ_s, ϕ_s) in the coordinate shown in Figure 2**,** we can then write the sun's location (x_s, y_s, z_s) with respect to the center as:

$$(x_s, y_s, z_s) = (\sin\theta_s \cos(\pi - \phi_s), \sin\theta_s \sin(\pi - \phi_s), \cos\theta_s), \tag{2}$$

assuming that the distance between the sun and the center is one arbitrary unit. Similarly, the location of the CSPHOT (x_c, y_c, z_c) can be given as:

$$(x_c, y_c, z_c) = (\sin\beta \cos(\pi - \phi), \sin\beta \sin(\pi - \phi), \cos\beta). \tag{3}$$

Using Eqs. (2) and (3), the apparent solar zenith angle θ_s^*, defined as the angle between the sun and the CSPHOT, can be calculated by:

$$\begin{aligned}\cos\theta_s^* &= \sin\theta_s \sin\beta \cos(\pi - \phi_s)\ \cos(\pi - \phi) + \ \sin\theta_s \sin\beta \sin(\pi - \phi_s) \sin(\pi - \phi) + \cos\theta_s \cos\beta \\ &= \sin\theta_s \sin\beta \cdot \cos\phi_s \cos\phi + \sin\theta_s \sin\beta \cdot \sin\phi_s \sin\phi + \cos\theta_s \cos\beta \\ &= \sin\theta_s \sin\beta \cos(\phi - \phi_s) + \cos\theta_s \cos\beta. \end{aligned} \tag{4}$$

As mentioned, retrievals are obtained through a look-up table approach. The look-up table is a function of cloud properties, surface albedo and solar zenith angle. For zenith radiance collected from a stable platform, the true solar zenith angle θ_s is used to construct the look-up table. In contrast, if the platform is not stable, then the apparent solar zenith angle θ_s^*, rather than θ_s, is used for look-up table constructions to account for the off-zenith effects.

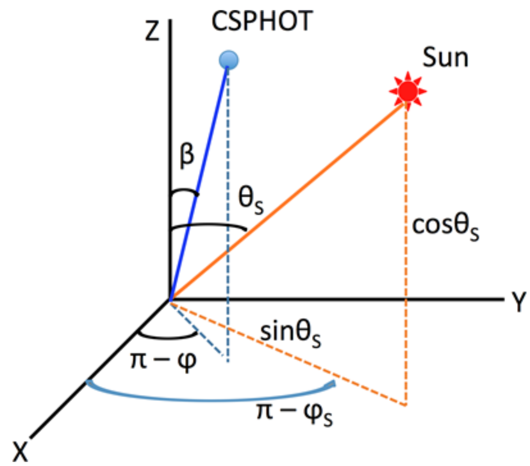

Figure 2. The coordinate used in deriving the beam angle of the CSPHOT pointing direction

3.0 Lessons Learned

During the campaign, CSPHOT was protected from soot and sea spray as much as possible. The instrument was in park (pointing down) with the collimator covered by a plastic bag before soot release. CSPHOT was cleaned in the early morning every day and its wet sensor was checked once a week. Post-campaign maintenance has shown that there was some dust on the internal filters of the sensor head, so we cleaned the filters. The instrument was re-assembled; the internal components were realigned as needed, and the tracking was tuned.

Cloud-mode measurements taken from late July to September are invalid for two reasons. The first is that the wet sensor failed due to sea-salt deposits that interfered with the signal. Generally, this would cause the wet sensor parameter to be set to 1 (“on”) continuously, preventing the instrument from taking measurements. We have learned that the fix was to disconnect the wet sensor and have the technicians manually turn off auto-mode when rain or rough seas were expected. We believe that the long-term solution is to find a way to use other sources of precipitation data from other instruments and send a signal to the instrument via the PC.

The second reason is that the CSPHOT unit deployed in the campaign was an older unit and needed to be replaced. This unit has been in service since 1998. Since this campaign was our first time deploying CSPHOT onboard a ship, we chose to use an older instrument in case of damage due to high winds, ship motion, and other unexpected circumstances. We suspect that there may have been prior issues with the control box and sensor head due to aging components. This particular unit has been repaired twice since MAGIC due to failing components, and it is strongly recommended that this instrument be replaced with a newer unit. It would also be advised to have a spare available for future deployments.

4.0 Results

A principal investigator (PI) product from this campaign is available via the campaign web page (see Section 1), providing retrieved cloud optical depth, effective radius, associated uncertainty every 5 seconds, and the number of successful retrievals among 40 ensembles generated with various perturbations in zenith radiance and surface albedo. Note that in cloud mode, zenith radiances were taken every 10 seconds by sun and sky radiometers. Retrievals based on sun radiometer measurements are reported first in each 10-second time interval, followed by retrievals from sky radiometers, resulting in 5-second resolution retrievals. Additionally, as described in Section 2.0, the mean retrieval and its uncertainty are estimated based on 40 ensembles. We have found that the retrieval is associated with higher confidence when the corresponding number of successful retrievals among these 40 ensembles is greater than 15.

4.1 Statistics

Figure 3 shows histograms of retrieved cloud optical depth and effective radius, with a total sample size of 83,500. The mean optical depth is about 13; the histogram peaks at 5–10 optical depths, generally agreeing with satellite observations over the North Pacific (Marchand et al. 2010). The mean cloud effective radius is 10 μm with a histogram peaking at 8–10 μm, which is somewhat smaller than those observed from in-situ measurements (Miles et al. 2000) for marine stratus and stratocumulus. Further investigation is needed to identify the sources of the discrepancy in effective cloud radius.

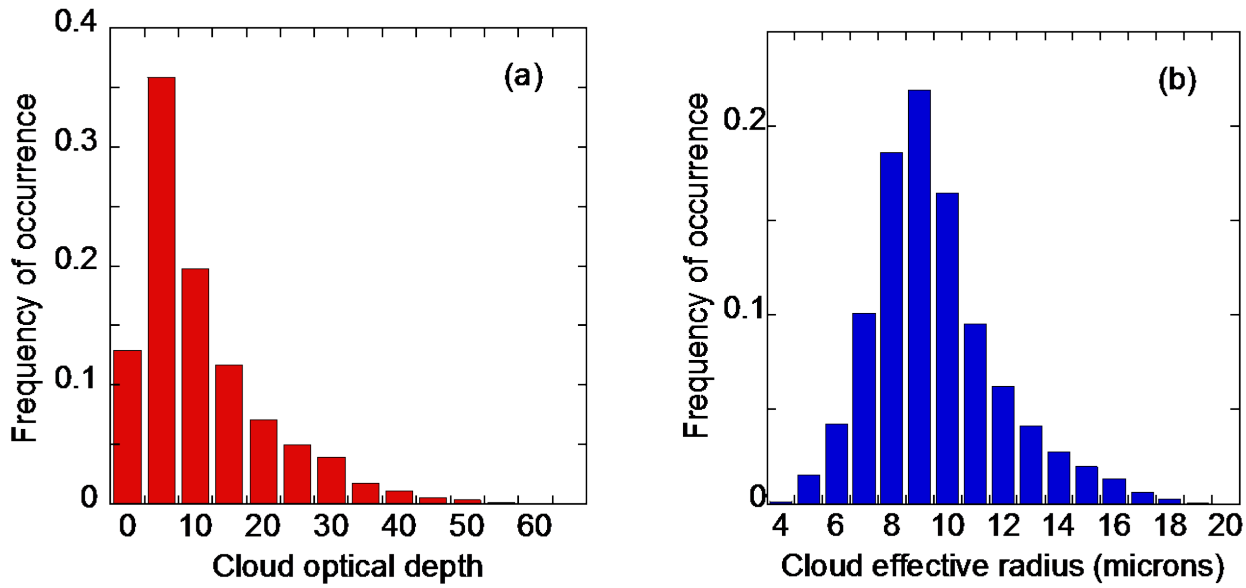

Figure 3. Histograms of retrieved (a) cloud optical depth and (b) effective radius during Leg 10–Leg 15 of the MAGIC field campaign

4.2 Synergy with Radar/Lidar Observations

Leveraging a synergy between cloud radar and HSRL observations, cloud-mode measurements from the campaign have played an important role in Fielding et al. (2015) for retrieving cloud and drizzle properties (as shown in Figure 4). Potential applications of these retrievals are diverse, including investigations into the covariance between cloud and drizzle, precipitation initiation, aerosol effects on drizzle suppression and the role of precipitation in cloud field organization and variability.

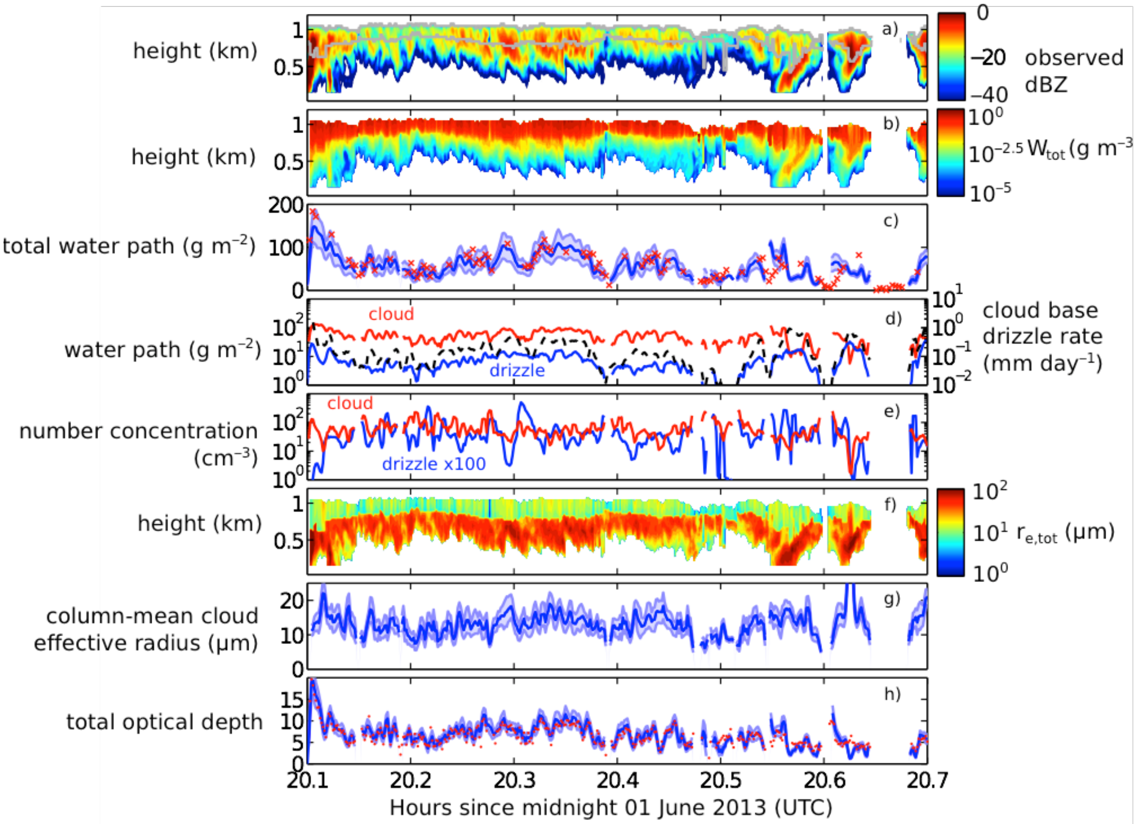

Figure 4. Retrieved Cloud Properties on 01 June 2013 during MAGIC in Predominantly Drizzling Conditions. Panels show time series of a) observed KAZR radar reflectivity factor, b) retrieved total water content, c) retrieved total water path from ENsemble ClOud REtrieval (ENCORE) (blue line) and the microwave 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 cloud-mode radiance only retrieval (red dots). The blue shading represents one standard deviation uncertainty in the retrieval (Fielding et al. 2015).

4.3 Further Research Opportunities

There are a number of other research opportunities using zenith radiance measurements and corresponding cloud retrievals from this campaign. First, zenith radiance is compared to measurements from the new ARM Shortwave Spectrometer (SAS-Ze) and other spectrometers, which helps resolve calibration issues and investigate cloud and aerosol properties in the transition zone between cloudy and clear regions. Second, cloud optical depth has been one of the key parameters in the study of aerosol indirect effects (McComiskey et al. 2009). Our retrievals have been used to calculate cloud droplet number concentration to quantify its dependency on cloud condensation nuclei (Painemal et al. 2015); they can also be used to quantify precipitation susceptibility for studying cloud-aerosol-precipitation interactions.

5.0 Publications from the Campaign

5.1 Journal Articles/Manuscripts

Fielding, MD, J-YC Chiu, RJ Hogan, G Feingold, E Eloranta, EJ O'Connor and MP Cadeddu. 2015. "Joint retrievals of cloud and drizzle in marine boundary layer clouds using ground-based radar, lidar and zenith raidances," *Atmospheric Measurement Techniques. Discuss* 8:1833–1889, doi:10.5194/amt-8-2663-2015.

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Fielding, M, J-YC Chiu, RJ Hogan, G Feingold, E Eloranta, EJ O'Connor and MP Cadeddu. 2015. "MAGIC at Every Level: Vertically Resolved Cloud and Drizzle Properties Using ENCORE," *Presented at Atmospheric System Research (ASR) Science Team Meeting*, Vienna, Virginia.

Gregory L, Wagener R, and L Ma. 2014. "Cimel sunphotometers: Highlights from Recent Deployments and Instrument Advancements for Cloud Mode Observations for Ship-Based Deployments," *Presented at Atmospheric System Research (ASR) Science Team Meeting.* Potomac, Maryland.

Marshak, A, W Yang, P McBride, C Flynn, S Schmidt, J-YC Chiu, and E Lewis. 2015. "Analysis of Shortwave Spectrometry During MAGIC," *Presented at Atmospheric System Research (ASR) Science Team Meeting*, Vienna, Virginia.

Painemal, D, C Yost, J-YC Chiu, P Minnis, and M Cadeddu. 2015. "Satellite and ship-based estimates of cloud-aerosol interactions during MAGIC campaign, plenary talk, *Presented at Atmospheric System Research (ASR) Science Team Meeting*, Vienna, Virginia.

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Fielding, M, J-YC Chiu, RJ Hogan, G Feingold, E Eloranta, EJ O'Connor and MP Cadeddu. 2015. "MAGIC at Every Level: Vertically Resolved Cloud and Drizzle Properties Using ENCORE," *Presented at Atmospheric System Research (ASR) Science Team Meeting*, Vienna, Virginia.

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