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Key Points:
- The methods developed in Wu et al. (2020) were used to retrieve maritime cloud and drizzle microphysical properties during MAGIC.
- From California to Hawaii, cloud layer became elevated, broken, and less stable; cloud fraction decreased; increase in \( r_{\text{m,d}} \).
- Except \( LWC_c \), which is about equal, mean cloud and drizzle microphysical properties during MAGIC are greater than those at ENA site.

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Maritime Cloud and Drizzle Microphysical Properties Retrieved From Ship-Based Observations During MAGIC

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Abstract
The Marine ARM GPCI Investigation of Clouds (MAGIC) field campaign provided a wealth of information looking at the stratocumulus to cumulus transition (SCT) over the Eastern-North Pacific (ENP), however, the lack of cloud in situ measurements gave limited information. Using the observations of Marine W-band ARM cloud radar, ceilometer, and three-channel microwave radiometer onboard the ship, we retrieve the single-layer, low-level cloud-droplet effective radius and drizzle median radius (\( r_c \) and \( r_{\text{m,d}} \)), number concentration (\( N_c \) and \( N_d \)), and liquid water content (\( LWC_c \) and \( LWC_d \)) using the methods in Wu et al. (2020, https://doi.org/10.1029/2019JD032205). Based on the results during MAGIC, we found that both cloud base and top heights increase approximately 0.75 km from Los Angeles (LA) until cloud breakup (CB) before leveling off. Low cloud fractions (CFs) ranged from ~85% halfway between LA and CB to ~20% near Hawaii. Retrieved \( r_c \) values decreased approximately 2 \( \mu \)m from peak CF to Hawaii while \( r_{\text{m,d}} \), increased more than 20 \( \mu \)m over the same path. Mean values of \( r_c \), \( r_{\text{m,d}}, N_c, N_d, LWC_c, \) and \( LWC_d \) during MAGIC are 12.1 \( \mu \)m, 55.8 \( \mu \)m, 97.9 cm\(^{-3}\), 0.09 cm\(^{-3}\), 0.40 g m\(^{-3}\), and 0.05 g m\(^{-3}\), respectively. Compared to the mean values of the Azores in Wu et al. (2020, https://doi.org/10.1029/2019JD032205), the mean cloud and drizzle microphysical properties during MAGIC, except \( LWC_c \) which is roughly equal, are greater due to higher liquid water path and warmer sea surface temperature. This information allows for a better understanding of the SCT over the ENP and can be used to better improve model simulations.

1. Introduction
Low-level stratiform clouds have been a topic of considerable interest since the publication of the classic paper describing their physics (Lilly, 1968) because the radiative effect of these clouds contributes to one of the largest uncertainties in climate modeling (IPCC, 2013). They have significant effects on the hydrological cycle and the Earth’s radiation budget and consequently on the regional and global climate (Garreaud et al., 2001; Hartmann et al., 1992; Klein & Hartmann, 1993; Nakajima et al., 2010; Ramathan et al., 1989; Stephens et al., 2015; Wood & Hartmann, 2006). These clouds strongly reflect incoming shortwave (SW) radiation, substantially reduce the SW radiation absorbed by the Earth’s surfaces (Hartmann et al., 1992; Randall et al., 1984; Slingo, 1990), and exert complex feedbacks on the climate system (Hang et al., 2019; L’Ecuyer et al., 2019; Stephens, 2005; Wood, 2012).

The subtropical low clouds located on the east side of the oceanic subtropical highs are maintained by subsidence in the descending branch of the Hadley circulation (Klein & Hartmann, 1993). They occur in semipermanent sheets over the cold eastern ocean basins. For example, the low cloud fractions (CFs) over the subtropical oceans near California and Southern Africa are more than 60% and can reach up to 80% over the South-East Pacific near Peru and Northern Chile. The stratocumulus to cumulus cloud transition (SCT) commonly occurs in subtropical ocean’s marine boundary layer (MBL). Stratocumulus (Sc) clouds, in particular, encompass a vast areal extent, ranging from 40% to 60% of cloud cover over eastern subtropical oceans (Wood, 2012), in which Sc plays an important role in the surface radiation budget. Clouds perform two important roles in helping to regulate the climate: (1) reflecting incoming solar radiation back to space to produce cooling and (2) absorbing and reemitting longwave radiation emitted from the Earth’s surface to produce warming. Different clouds have different radiation effects. For example, Sc has a strong net radiation cooling effect resulting from higher solar reflectance due to larger areal coverage and little interaction with outgoing radiation due to their lower altitude (Chen et al., 2000; Wood, 2012). Cumulus (Cu) clouds, on the other hand, show a weaker cooling effect due to their smaller areal extent although their solar reflectance is also very high. Good representation of the SCT is important in climate models to accurately represent the radiation budget.
The SCT cloud boundaries, cloud and precipitation properties over the Azores, were observed and documented during the 1992 Atlantic Stratocumulus Transition Experiment (B. A. Albrecht et al., 1995) and over the southeast Pacific during the VAMOS Ocean–Cloud–Atmosphere–Land Study Regional Experiment (VOCALS-REx) in October–November 2008 (Bretherton et al., 2010; Wood et al., 2011). Bretherton and Wyant (1997) and Wyant et al. (1997) developed a commonly accepted but simple theoretical model for understanding the SCT, in which the advection of cloud systems from Sc to Cu over an increasing sea surface temperature (SST) allows for the decoupling of the Sc layer. The decoupling is seen with the formation of a weak stable layer created beneath Sc. This separates the MBL into a Cu favored, surface flux driven convection and a Sc favored, longwave radiative cooling convection. As rising Cu becomes more vigorous with increasing SST, they can penetrate the stable layer and into the cloud top inversion layer. Much drier air is typically seen above this cloud top inversion (Bretherton et al., 2010) leading to entrainment of dry air and the decline of Sc.

Despite understanding the basic mechanisms causing the SCT, many uncertainties remain as well as accurately simulating these clouds in climate models (Teixeira et al., 2011). Drizzle, while not included in Wyant et al. (1997) model, frequently occurs in MBL clouds and has been found to influence this transition zone (Paluch & Lenschow, 1991; Yamaguchi et al., 2017), as well as cloud duration (B. A. Albrecht, 1989). Climate models consistently produce precipitation too frequently and too light for subtropical MBL clouds (Bony & Dufresne, 2005; Dolinar et al., 2015; Dong et al., 2021; Donner et al., 2011; Schmidt et al., 2006; Soden & Vecchi, 2011). Better representing precipitation events in general circulation models will allow for a more accurate representation of clouds in the MBL. With an improved understanding of cloud properties, one can better represent these clouds and their radiation effects, leading to increased accuracy of climate models.

Determining the distributions and profiles of cloud and drizzle microphysical properties in MBL clouds is critical in understanding cloud-to-rain conversion and growth processes (e.g., Dong et al., 2021). For cloud formation, cloud droplets form near cloud base and grow through condensation as they rise. The formation of drizzle is initiated once cloud droplets reach a particular size so that the force of gravity surpasses the buoyancy force. As these drizzle drops fall, they begin the collision-coalescence process with cloud and smaller drizzle droplets to grow in size. The rate at which drizzle will grow, in part, depends on the liquid water content (LWC) in the cloud. Hence, it is important to have ground-based observations to retrieve these properties at a high temporal resolution to better understand MBL cloud evolution.

In this study, the retrieval methods developed by Wu et al. (2020) were adapted to retrieve MBL cloud and drizzle microphysical properties over the Eastern-North Pacific (ENP) during the Marine ARM (Atmospheric Radiation Measurement) GPCI (Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) Pacific cross-section intercomparison) Investigation of Clouds (MAGIC) campaign. In the newly developed retrieval methods by Wu et al. (2020), both cloud and drizzle microphysical properties were retrieved and validated from aircraft in situ measurements during the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) campaign, which will be discussed in the following section. The ship-based measurements during MAGIC campaign are very similar to those during ACE-ENA and provide all the inputs for the cloud and drizzle microphysical property retrievals. During MAGIC, MBL clouds range from 20% to 75% of cloud type seen over the measurement region and frequently produce precipitation (Zhou et al., 2015).

Since the new retrieval methods are applicable to low-level liquid-phase stratus, Sc and shallow cumulus clouds (cloud tops lower than 3 km), the new cloud and drizzle observations and retrievals during MAGIC will provide valuable insight to investigate the SCT over the ENP. The retrieved microphysical properties will allow model evaluation and help determine any model errors. The paper will be organized as follows. Section 2 will give an overview of instrumentations during MAGIC and a brief description of the retrieval algorithm. Section 3 will first discuss how the cloud and drizzle properties change for a selected SCT case. Second, the statistical retrieval results from all cases during MAGIC will be provided. Third, the longitudinal averaged cloud and drizzle properties across the ENP will be discussed. Lastly, the similarities and differences of cloud and drizzle properties between MAGIC and ACE-ENA will be investigated. A summary and conclusion will be given in Section 4.
2. Data and Methodology

The MAGIC field campaign was conducted from October 2012 until September 2013 with the goal of better understanding the SCT over the ENP. Multiple in situ and remote-based instruments of ARM mobile facility (Mather & Voyles, 2013; Miller et al., 2016) were aboard the Horizon Lines cargo ship, Spirit, traveling to and from Los Angeles (LA), California and Honolulu, Hawaii (33.7°N, −118.2°E and 21.3°N, −157.8°E). The MAGIC campaign was unique because its observations were collected and processed, as well as retrieved in this study, over a path more than 4,000 km long during a period of nearly a year, providing a large areal and seasonal variation. A total of 20 round trips were completed with each trip labeled as “LegxxA” traveling toward Honolulu with clouds transitioning from Sc to Cu or “LegxxB” traveling toward LA with the opposite cloud transition. Figure 1 shows satellite imagery of typical SCT during MAGIC with Spirit’s track, shown in red, moving directly through this transition. Uniform Sc is observed from coastline until near −135°E longitude where the transition to Cu occurs and remains until Hawaii. While the exact position of the SCT may vary slightly for each trip, this is a very typical setup in the ENP. Using the instruments aboard Spirit, this study will show the retrieved microphysical properties of the SCT during MAGIC.

The primary measurements used in this study are from W-band cloud radar, ceilometer, microwave radiometer, and radiosonde soundings, and a full list of instrumentation during MAGIC can be found at https://www.arm.gov/research/campaigns/amf2012magic. All these measurements are averaged into 5 min to fulfill the requirement of the retrieval algorithm (Wu et al., 2020). A brief description of the retrieval algorithm will be followed, and a summary of the retrieval will be described too.

2.1. Ship-Based Instrumentation

A vertical pointing Marine W-band Atmospheric Radiation Measurement (ARM) Program Cloud Radar (MWACR) 95 GHz profiling Doppler radar was used to obtain cloud boundary and hydrometers vertical distribution during MAGIC. The MWACR has a vertical resolution of 21 m and a temporal resolution of about 0.2 s within 1 dBZ uncertainty (Kollias et al., 2016). In addition to the high temporal resolution, the 5-min averages help compensate for ship motion. The highest radar range gate with detectable signal was used to detect cloud top heights (−40 dBZ used here). A reflectivity profile was labeled as drizzling if the reflectivity at cloud base exceeds −37 dBZ (Wu et al., 2015). Figure 2a shows MWACR reflectivity for a portion of Leg15A with an obvious SCT event in which the cloud layer monotonically increases from ~0.5 km at LA to ~2.0 km close to Hawaii. It was uniform and overcast stratus cloud layer with little or virga drizzling from
LA to ~−122°E, then became Sc with heavy drizzling from −122°E to −129°E, and finally, it became thin and thick, and broken after passing −129°E. The cloud thickness (cloud top–base) did not change too much but the entire layer was elevated from LA to Hawaii and changed from overcast to broken. Note that the MWACR was temporarily turned off between −134°E and −135°E longitude. A 910-nm wavelength laser ceilometer (Vaisala model CT25K) was used to determine the cloud base (Ghate & Cadeddu, 2019).

The profiles of atmospheric temperature and relative humidity were obtained from the radiosonde soundings launched on the ship from LA to Hawaii. As seen in Figure 2b, the potential temperatures were nearly constant from the surface to the increased cloud top from LA to Honolulu, indicating the cloud layer was a well-mixed layer (Dong et al., 2015). Both potential temperature and relative humidity profiles corresponded well with the radar-lidar measured cloud boundaries. The three-channel microwave radiometer

Figure 2. An example of showing Leg 15A measurements from Los Angles to −150°E longitude during the period July 21, 2013 to July 23, 2013. (a) Reflectivity from Marine W-band ARM cloud radar (MWACR), block dots represent cloud base derived from laser ceilometer. Note MWACR was temporarily turned off from −134°E to −135°E. (b) Profiles of potential temperature (black) and relative humidity (blue) from every-other soundings launched, with the starting longitude also shown. (c) Cloud liquid water path (LWP) retrieved from three-channel microwave radiometer measured brightness temperatures (black) and lower tropospheric stability (red) calculated from sounding in (b).
(MWR3C) measures brightness temperatures at 23.8, 30, and 89 GHz was used to retrieve cloud liquid water path (LWP) using the physical retrieval method with the additional use of radiosonde soundings and ceilometer-determined cloud base height with an uncertainty of <20 g m⁻² (Cadeddu et al., 2013; Painemal et al., 2016). Only the LWP values between 20 and 700 g m⁻² were used to avoid wet-random issues in this study.

### 2.2. Retrieval Methods

The retrieval methods, developed by Wu et al. (2020), determine cloud-droplet effective radius ($r_c$), drizzle median radius ($r_{md}$), cloud and drizzle number concentration ($N_c$ and $N_d$), and liquid water content ($LWC_c$ and $LWC_d$). It assumes lognormal distribution for cloud droplet size distribution (DSD) and normalized gamma distribution for drizzle DSD. The retrieved product agrees well with in situ measurements, both in time series and vertical profiles. Taking aircraft measurement as cloud truth, the median retrieval uncertainties are estimated as ~15% for $r_c$, ~35% for $N_c$, ~30% for $LWC_c$ and $r_{md}$, and ~50% for $N_d$ and $LWC_d$. While this retrieval provided valuable information to the Azores site, it has yet to be used elsewhere.

The retrieval method starts with decomposing cloud and drizzle reflectivity in a cloud layer from MWACR reflectivity measurements. From the in situ data measured during ACE-ENA, calculated cloud droplet reflectivity ranges from −40 to −12 dBZ at 35 GHz, and calculated drizzle reflectivity shows almost no values below −32 dBZ. Additionally, cloud droplets growing by condensation reaching their maximum radius and reflectivity just below the cloud top. Above this height, cloud top entrainment typically keeps cloud droplets below −32 dBZ. Additionally, cloud droplets growing by condensation reaching their maximum radius and reflectivity just below the cloud top. Above this height, cloud top entrainment typically keeps cloud droplets below −32 dBZ. Cloud droplets were defined to reach a maximum reflectivity of −15 dBZ for ACE-ENA and reflectivity just above cloud base from the drizzle reflectivity just below the cloud base. With the cloud reflectivity already known, the in-cloud drizzle reflectivity is simply MWACR reflectivity minus the cloud reflectivity. For here, cloud and drizzle reflectivity still need to be separated from cloud base to just below cloud top. A cloud reflectivity profile is first constructed from cloud base to −15 dBZ under the assumption of linear increasing $LWC_c$ and constant $N_c$ to easily calculate cloud reflectivity. This is done assuming only drizzle reflectivity is seen at the first MWACR gate below cloud base and both cloud and drizzle reflectivity are seen at the first gate above cloud base. The first cloud reflectivity is calculated by subtracting the MWACR reflectivity minus the drizzle reflectivity just above cloud base from the drizzle reflectivity just below the cloud base. With the cloud reflectivity profile obtained, the in-cloud drizzle reflectivity is simply MWACR reflectivity minus the cloud reflectivity.

For drizzling clouds, drizzle properties below the cloud base are calculated using a widely used method developed by O’Connor et al. (2005) with drizzle PSD represented by a normalized Gamma distribution. In-cloud drizzle properties are calculated from the results of Wood (2005) and similar to Fielding et al. (2015) where normalized drizzle number concentration increases linearly with cloud height and the shape parameter is assumed as the average of those below cloud base. This then allows for the calculation of $r_{md}$, $LWC_d$, and drizzle cloud liquid water path ($LWP_d$ and $LWP_d$).

Lastly, the cloud PSD is represented by a lognormal distribution (Dong et al., 1997, 1998, 2014; Frisch et al., 1995; Miles et al., 2000) with the logarithmic width set to 0.38, the average value from aircraft in situ measurements over different ocean basins for MBL clouds (Miles et al., 2000). $LWC_c$ is calculated using cloud reflectivity and a first guess of $N_c$ equal to 60 cm⁻³. Both $LWC_c$ and $N_c$ can then be scaled based on the calculated $LWP_c$. Knowing $N_c$ and $LWC_c$ then allows for the calculation of $r_c$. For further details regarding the retrieval methods, please read Wu et al. (2020).

Of additional note, while a Ka-band ARM zenith radar (KAZR) was used in the original retrieval study, as previously mentioned, this study used MWACR for the retrieval algorithm. As seen in Figure 3, probability density functions (PDFs) of KAZR and MWACR 5-min averages are shown for in-cloud reflectivity for measurements below 3 km during MAGIC. In total, 262,857 five-min samples were used for MWACR and 199,151 samples for KAZR were used, with the larger sample number from MWACR due to a higher vertical resolution. KAZR shows a consistent shift of higher reflectivity values compared to MWACR, with mean values of −15.6 and −23.9 dBZ, respectively. Using KAZR reflectivity measurements in the methods of Wu et al. (2020), the retrieved cloud and drizzle microphysical properties were much higher than what are typically expected in MBL clouds. Therefore, we decide to use MWACR reflectivity measurements for the retrieval. Compared to the ACE-ENA, the mean MWACR reflectivity is about 10 dBZ larger, the difference...
comes from reflectivity dependence on particle size to the sixth power. Precipitating clouds during MAGIC were found to occur 22% more frequently than ACE-ENA (47%), leading to the higher dBZ values during MAGIC. As expected, the overall mean retrieved cloud and drizzle microphysical properties during MAGIC should be greater than those during ACE-ENA. Since the retrieval methods rely on reflectivity for drizzle initiation and the difference below and above cloud base, the higher dBZ values during MAGIC should not largely affect cloud property retrievals but may impact drizzle property retrievals. Hence, there is greater confidence in using MWACR for the retrieval methods.

A total of 159 days of retrieved cloud and drizzle microphysical properties during MAGIC were used in this study. This includes 45 days during November and December 2012 with the rest occurring from May to September 2013; note that no trips occurred from mid-January to April 2013 due to ship maintenance. All cases selected in this study are low-level Sc or Cu clouds with cloud tops below 3 km, and their LWPs less than 700 g m\(^{-2}\). Of 159 days, there are 1,040 h of cloud retrievals and 718 h of drizzle retrievals.

### 3. Results and Discussions

#### 3.1. Cloud and Drizzle Microphysical Properties

##### 3.1.1. A Selected SCT Event

Figures 1 and 2 show the spatial and vertical variations of the selected SCT event, occurring for Leg15A (July 20, 2013 to July 25, 2013) during MAGIC. Both satellite visible imagery in Figure 1 and radar reflectivity in Figure 2a clearly show the stratocumulus to cumulus transition near −138°E longitude. Radar reflectivity shows consistently drizzling Sc as evidence of reflectivity below cloud base. Due to increasing SST, cloud top height increases from about 0.5 km near California to stalling around 2 km until Hawaii. As the ship heads westward, the Sc breaks up, and drizzling Cu clouds form with higher reflectivity values for both in and below cloud. Further evidence of this transition is seen in Figure 2b where potential temperature (\(\theta\)) from every-other soundings taken throughout the leg shows a well-mixed MBL (Dong et al., 2015) and a strong capping inversion directly above cloud tops, with relative humidity showing much drier air
above this inversion. Heading toward Hawaii, this inversion becomes weaker as less Sc occurs to produce less outgoing longwave radiation and less cooling. The formation of the less stable layer is also seen near 0.8 km starting near −139°E longitude and remains heading westward, with a weak inversion and sharp change in relative humidity. To further quantify it, lower tropospheric stability (LTS) was calculated from soundings where LTS represents the $\Theta$ difference between 700 mb and the surface. As seen in Figure 2c, LTS decreases heading toward Hawaii, indicating that the air is becoming less stable westward, which partially attributes to the warming SST and weakening of the cloud top inversion layer. Also shown in Figure 2c is LWP, Sc regions show LWP staying mostly below 400 g m$^{-2}$ with values dropping to near zero westward of −138°E but spiking for drizzling Cu.

Using the retrieval methods described in Section 2.2, Figure 4 shows the retrieved cloud properties on the left and retrieved drizzle properties on the right for the selected case shown on Figures 1 and 2. For the Sc regions, $N_c$ stays roughly constant at 90 cm$^{-3}$ and with $r_c$ and $LWC_c$ both seeing a steady increase with height until maxing near cloud top. For the same region, $r_m,d$ does not see an obvious change with height but both $N_d$ and $LWC_d$ have highest values for in-cloud, however. Starting near −135°E until complete cloud breakup (CB) near −139°E, microphysical properties can be seen for this transition. Mean values of $r_c$ decrease from ~14 to ~9 μm while $N_c$ values increase to near 140 cm$^{-3}$ over the region followed by a decrease. The overall effect, however, is a decrease in $LWC_c$ from ~0.6 to ~0.2 g m$^{-2}$. Drizzle also changes over this region as decreasing cloud thickness inhibits drizzle collision-coalescence as indicated by increased $N_d$ and decreased $r_m,d$ for in-cloud. As a result, most of the drizzles evaporated before reaching the surface. Heading westward, drizzling Cu forms with larger $r_c$ and $r_m,d$ and higher $LWC_c$ and $LWC_d$ compared to those over the Sc regions.

Based on analyzing the microphysical properties of the selected SCT, one can better understand the processes of SCT. With decreasing LTS moving westward, dry air aloft is more easily entrained into the cloud layer as evidence of the decreasing $LWC_c$. Zhou et al. (2015) suggested that these sudden CBs likely occur from synoptic conditions causing subsidence over these regions and this appears to be the case here. As seen in

Figure 4. Decomposed cloud and drizzle reflectivity and retrievals during the portion of Leg15A. (a) Cloud reflectivity, (b) cloud-droplet effective radius, $R_c$, (c) cloud-droplet number concentration, $N_c$, and (d) cloud liquid water content, $LWC_c$. (e–h) The same as (a)–(d) but for drizzle properties. Black dots represent cloud base heights. Note that drizzle median radius was used in this study and shown in (f).
Figure 1, a low-pressure system near 37°N latitude and −158°E longitude creates diverging surface winds over the transition region to help entrain the dry air aloft and decrease \( LWC_c \). Increasing SST westward, however, allows more vigorous surface convection, which may generate more Cu as seen with increased \( r_c \) and \( r_m \).

### 3.1.2. Statistical Results

PDFs are shown in Figure 5 where both \( r_c \) and \( N_c \) have a normal distribution with a range of 4–20 µm and 20–200 cm\(^{-3}\), respectively, with the mean values of 12.1 µm and 97.9 cm\(^{-3}\). \( LWC_c \) is positively skewed with a long tail toward large values and its mean value is 0.40 g m\(^{-3}\). All drizzle properties are positively skewed with a long tail toward large values, and their mean values are 55.8 µm, 0.09 cm\(^{-3}\), and 0.05 g m\(^{-3}\), respectively. It is worth to mention that the standard deviations of \( N_d \) and \( LWC_d \) are even larger than their means, implying that there are more relatively larger values compared to their means. Note that the mean radius of drizzle is about 3–4 times of cloud \( r_c \), whereas the cloud \( N_c \) and \( LWC_c \) are 1,000 and 10 times of drizzle \( N_d \) and \( LWC_d \).

To investigate their vertical distributions, all retrieved cloud and drizzle microphysical properties during MAGIC are normalized from drizzle base to cloud base and top as shown in Figure 6 with the mean values (solid lines) and one standard deviation (shaded regions). Normalized heights \( z = \frac{z - z_{\text{base}}}{z_{\text{top}} - z_{\text{base}}} \) are given.
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with drizzle base equal to −1, cloud base equal to 0, and cloud top equal to 1. As shown in Figures 6a–6c, \( r_c \) and \( LWC_c \) both rise steadily with height as rising cloud droplets grow by condensation until reaching a maximum near \( z_\text{t} \sim 0.75 \), and \( N_c \) staying constant around 98 cm\(^{-3}\) due to the retrieval assumption. Above the maximum \( r_c \) and \( LWC_c \) height, entrainment and precipitation scavenging typically lead to evaporating and shrinking of cloud-droplet effective radius and the decrease in \( LWC_c \). The bottom panel of Figure 6 shows the vertical distributions of drizzle properties in which \( r_m \), \( d \) increases monotonically from the cloud top to the cloud base, reaching the maximum near the cloud base, and remains nearly invariant toward the drizzle base. \( N_d \) slightly decreases from the cloud top to the cloud base, followed by a sharp decrease just below the cloud base due to net evaporation and a steadily decreasing number concentration hereafter. \( LWC_d \) is dependent on both \( r_m \) and \( N_d \), increases from the cloud top to \( z_t \sim 0.3 \) (maximum), and then decreases dramatically toward the cloud base and further down to the drizzle base. These results suggest that the growing process of drizzle drops is mostly going through the collision-coalescence process with cloud droplets and drizzle drops within the cloud layer and with other drizzle droplets below the cloud base.

### 3.2. Longitude Variation of Cloud and Drizzle Properties

One of the goals of this study is to examine how cloud and drizzle microphysical properties vary with longitudes from LA to Honolulu. Zhou et al. (2015) first looked at how cloud properties, such as cloud type, cloud height, and estimated inversion strength, vary with longitude during MAGIC. With the available new

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**Figure 6.** Normalized profiles of retrieved mean cloud (top row) and drizzle (bottom row) microphysical properties in normalized height \( z_i = \frac{z - z_{\text{base}}}{z_{\text{top}} - z_{\text{base}}} \) during MAGIC. Shown with drizzle base as −1, cloud base as 0, and cloud/drizzle top as 1. Solid lines represent the means and gray shaded boundaries represent standard deviations.
retrievals of cloud and drizzle properties in this study, we can use these comprehensive data sets to investigate the cloud and drizzle macrophysical and microphysical properties during MAGIC, as well as their longitudinal variations. Normalized variations from just off-coast of LA (\(\sim -118^\circ\text{E}\)) to CB and from CB to Hawaii (\(\sim 158^\circ\text{E}\)) are used to investigate these changes. Here, CB is defined when hourly CF drops below 50%. In total, 15 legs with 92 days were used in these calculations as not every leg showed a SCT.

Figure 7 shows the normalized longitude cloud base and top heights, CF, LWP and cloud condensation nuclei (CCNs at 0.2% supersaturation) and their corresponding standard deviations (shaded green). Both cloud base and top heights increase approximately 0.75 km from LA until around CB and then level off until Hawaii. Cloud thickness, however, shows no trend with longitude. The radar-lidar derived low-level CFs (cloud tops below 3 km) increase from 50% near LA to \(\sim 85\%\) halfway between LA and CB then fluctuate slightly and decrease to \(\sim 20\%\) near Hawaii. The LWPs keep nearly 100 g m\(^{-2}\) except for near LA and Hawaii but see an overall decrease. CCNs concentrations reach the maximum of 300 cm\(^{-3}\) near LA due to the influence of continental and anthropogenic aerosols, monotonically decrease toward CB, and then level off from CB to HI at \(\sim 100\text{ cm}^{-3}\).

Similar to Figure 7, Figure 8 shows the normalized longitude variations of cloud and drizzle microphysical properties during MAGIC. Except for the regions near the coastline of California which may be impacted by continental aerosols, \(r_{\text{c}}\) peaks near CF maximum in Figure 7b with a value of \(\sim 13\ \mu\text{m}\) then monotonically decreases westward and reaches a minimum of \(\sim 11\ \mu\text{m}\) near Hawaii. As suggested by Zhou et al. (2015), entrainment was the dominating factor triggering decoupling during MAGIC, the increased entertainment
from stronger surface convection and decreasing LTS moving westward would help explain the decrease in $r_c$ as seen in Figure 8a. On the other hand, $r_{m,d}$ increases from $\sim 40 \mu m$ near CF maximum to $>60 \mu m$ just west of CB, that is, $r_{m,d}$ increases more than $20 \mu m$ heading toward Hawaii, with the largest change east of CB. Though cloud thickness changes little, the deepened cloud layer, especially east of CB, seen in Figure 7a would allow for additional drizzle drop falling time and increased collision-coalescence frequency with smaller drizzle particles, helping to explain the increased drizzle size. Additionally, despite the decreasing trend in $r_c$ in Figure 8a, as well as seen in the selected case above, drizzling Cu clouds can produce larger drizzle size relative to Sc.

$N_c$ is nearly invariant over the ship path, with values averaging near 100 cm$^{-3}$. Note that the mean $N_c$ values are nearly same as CCNs from CB to HI, presumably due to precipitation scavenging and more decoupled or lower LTS conditions. $LWC_c$ is the product of $r_c$ and $N_c$, thus it mainly follows the longitudinal variation of $r_c$, with peak values near 0.5 g m$^{-3}$ and reaching a minimum near 0.3 g m$^{-3}$. The normalized longitude variations of $N_d$ values are greater than 0.07 cm$^{-3}$ eastward of CB, and nearly invariant west CB with values between 0.06 and 0.08 cm$^{-3}$. This opposing relationship seen with $r_{m,d}$ helps to explain why $LWC_d$ is nearly invariant, averaging near 0.05 g m$^{-3}$, with small fluctuations over the same path.

3.3. Comparisons With ACE-ENA and Other Field Campaigns

Up to date, the retrieval methods developed in Wu et al. (2020) have yet to be implemented for other campaigns besides ACE-ENA. The use of this retrieval has allowed for a comparison of cloud and drizzle microphysical properties across different ocean regions although there are some potential issues, such as the radar reflectivity measurements during different field campaigns, the usability of the retrieval methods developed during ACE-ENA but applying for MAGIC, different regions, etc. It should mention that it is crucial to understand how cloud and drizzle properties change across ocean basins and what mechanisms control these properties. For example, differences in ocean temperature, aerosol sources, and meteorological factors all can contribute to cloud properties. While this paper only points out the differences between

Figure 8. Same as Figure 7 expect with cloud (left column) and drizzle (right column) microphysical properties over normalized path from LA to CB and CB to HI. Green shade region represents one standard deviation. LA, Los Angeles; CB, cloud breakup; HI, Hawaii.
ACE-ENA and MAGIC, future work can better determine the causes of these differences. As summarized in Wu et al. (2020) and listed in Table 1, the mean retrieved values of $r_c$, $r_{m,d}$, $N_c$, $N_d$, $LWC_c$, and $LWC_d$ are $10.9 \, \mu m$, $44.9 \, \mu m$, $70 \, cm^{-3}$, $0.07 \, cm^{-3}$, $0.21 g \, m^{-3}$, and $0.05 g \, m^{-3}$, respectively, during ACE-ENA. Besides $LWC_d$ which shows the same value, the retrieved cloud and drizzle microphysical properties during MAGIC are greater than those during ACE-ENA with differences of $1.2 \, \mu m$, $10.9 \, \mu m$, $27.9 \, cm^{-3}$, $0.02 \, cm^{-3}$, $0.19 g \, m^{-3}$, and $0.00 g \, m^{-3}$, respectively. The large values during MAGIC are most likely attributed to higher cloud LWPs ($115 g \, m^{-2}$ vs. $85 g \, m^{-2}$) and warmer SST near Hawaii causing stronger convection to generate both larger and more droplets, as well as $LWC_c$. Differences in aerosol concentration also likely affect $N_c$.

The vertical distribution of $r_c$ and $LWC_c$ during MAGIC is almost identical to those during ACE-ENA in which both $r_c$ and $LWC_c$ increase gradually with height, peaking near $z_i \sim 0.75$, then followed by a sharp decrease toward the cloud top. Drizzle properties, however, show some differences during these two field campaigns. The mean radius of drizzle drop peaked at the cloud base during ACE-ENA, while it was below the cloud base during MAGIC. The mean values of $N_d$ decreased from the cloud top to cloud base and then downward toward the drizzle base during ACE-ENA; however, they were nearly constant in clouds and decreased dramatically below the cloud base during MAGIC. Depending on both $r_{m,d}$ and $N_c$, $LWC_d$ showed closer resemblance but peaked at $z_i \sim 0.50$ during ACE-ENA and $z_i \sim 0.3$ during MAGIC. These differences are likely contributed to the decoupling of the MBL and the SCT during MAGIC, but further investigation is needed in the future.

The results during MAGIC (e.g., Figure 2) are also very similar to the results from other field campaigns. For example, B. Albrecht et al. (2019) found a similar SCT to Figure 2 from LA to Hawaii during Cloud System Evolution in the Trades field campaign. This deepening-warming process of decoupling westward was first proposed by Bretherton and Wyant (1997) where the planetary boundary layer (PBL) deepens westward as the surface temperature rises and the subsidence ebbs. Near the coast regions, Sc clouds are dominant and most are coupled with the surface and become decoupling offshore with the occurrence of drizzle. As the PBL deepens, cumuli develop beneath the Sc and form mesoscale cellular cloud complexes. Similar results were observed by AMF, aircraft carried cloud radar and GOES-10 satellite over SE Pacific during the multi-agency sponsored 2008 VOCALS-REx (Wood et al., 2011).

### 4. Summary and Conclusions

The retrieval methods developed by Wu et al. (2020) allowed for low-level, single-layer cloud and drizzle microphysical properties to be determined simultaneously. While the methods were developed and used for ACE-ENA, additional campaigns have yet to be investigated using this work. This study uses these methods to look at cloud and drizzle properties during the MAGIC field campaign in the ENP. The MAGIC campaign observed most clouds occurring within the MBL and frequently produced precipitation. Using the MWACR, ceilometer, and MWR3C placed onboard the Spirit cargo ship during MAGIC, 159 days of data were collected and retrieved using the methods of Wu et al. (2020). This accounted for 1,040 h of cloud properties and 718 h of drizzle properties to be retrieved. This has allowed an in-depth look at these properties along the SCT in the ENP.

The SCT is an important feature over this ocean basin and is one of the reasons why the MAGIC campaign was so valuable. The soundings launched and the retrieval outputs have verified that entrainment of dry air aloft is an important mechanism for initiating this cloud transitions. Decreasing LTS allows more mixing near cloud top and is reflected in the decrease of in $LWC_c$ seen as Sc begins to break up for the selected SCT case. Overall, for the 159 days, the retrieval was run, mean values were found to be $12.1 \, \mu m$, $55.8 \, \mu m$, $97.9 \, cm^{-3}$, $0.09 \, cm^{-3}$, $0.40 g \, m^{-3}$, and $0.05 g \, m^{-3}$ for $r_c$, $r_{m,d}$, $N_c$, $N_d$, $LWC_c$, and $LWC_d$, respectively. Mean

| Table 1 | Cloud and Drizzle Retrieved Values for MAGIC and ACE-ENA |
|---------|----------------------------------------------------------|
|         | $r_c$ ($\mu m$) | $N_c$ ($cm^{-3}$) | $LWC_c$ ($g \, m^{-3}$) | $r_{m,d}$ ($\mu m$) | $N_d$ ($cm^{-3}$) | $LWC_d$ ($g \, m^{-3}$) |
| MAGIC   | $12.1 \pm 3.3$ | $97.9 \pm 35.7$ | $0.40 \pm 0.36$ | $55.8 \pm 43.0$ | $0.09 \pm 0.17$ | $0.05 \pm 0.10$ |
| ACE-ENA | $10.9 \pm 3.7$ | $70 \pm 29.0$   | $0.21 \pm 0.21$ | $44.9 \pm 19.4$ | $0.07 \pm 0.09$ | $0.05 \pm 0.06$ |
normalized vertical profiles also showed $r_c$ and $LWC_c$ peaking with near cloud top and $r_{m,d}$ reaching a maximum just below cloud base.

Additionally, one of the goals of this study was to look at how these properties change with longitude. Normalized longitude variations of macrophysical cloud properties moving westward reveal cloud top and cloud base increase by $\sim 0.75$ km before leveling off, LWP staying near 100 g m$^{-2}$ but decreasing gradually, and CF fluctuating as much as 60% over this path. CCNs concentrations reach the maximum of 300 cm$^{-3}$ near LA due to the influence of continental and anthropogenic aerosols, monotonically decrease toward CB, and then level off from CB to HI at $\sim 100$ cm$^{-3}$. Normalized longitude variations of the retrieved drizzle microphysical properties showed $r_{m,d}$ seeing the largest change, with drops increasing by $\sim 20$ μm moving toward Hawaii, and can be explained by the increased cloud height. Also, worth mentioning is $r_c$ decreases $\sim 2$ μm heading westward, likely from increased entrainment, and is reflected by the decreasing $LWC_c$ seen, as $N_c$ is nearly invariant over this region.

Compared to the retrievals during ACE-ENA, the mean values during MAGIC show greater values for cloud and drizzle microphysical properties due to higher LWP and warmer SST. The vertical profiles of the retrieved cloud properties at the two sites are mimic each other but drizzle notable reaching maximum size just below cloud base at MAGIC versus at cloud base for ACE-ENA. Identifying the differences at the two sites is the first step to better determine the different mechanisms which control MBL clouds over these ocean basins. For instance, further research using these retrieval results will allow better understanding of cloud–aerosol interaction. By better understanding these processes over ENP, climate models can better stimulate these clouds, leading to a more accurate radiation budget and a better representation of the Earth system.

**Data Availability Statement**

The data can be downloaded from [https://adc.arm.gov/discovery/#/results/site_code::mag](https://adc.arm.gov/discovery/#/results/site_code::mag).

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