Investigation of the Diurnal Variation of Marine Boundary Layer Cloud Microphysical Properties at the Azores

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(Manuscript received 23 June 2014, in final form 29 August 2014)

ABSTRACT

A new method has been developed to retrieve the nighttime marine boundary layer (MBL) cloud microphysical properties, which provides a complete 19-month dataset to investigate the diurnal variation of MBL cloud microphysical properties at the Azores. Compared to the corresponding daytime results presented in the authors' previous study over the Azores region, all nighttime monthly means of cloud liquid water path (LWP) exceed their daytime counterparts with an annual-mean LWP of 140 g m^{-2}, which is ~30.9 g m^{-2} larger than daytime. Because the MBL clouds are primarily driven by convective instabilities caused by cloud-top longwave (LW) radiative cooling, more MBL clouds are well mixed and coupled with the surface during the night; thus, its cloud layer is deeper and its LWP is higher. During the day, the cloud layer is warmed by the absorption of solar radiation and partially offsets the cloud-top LW cooling, which makes the cloud layer thinner with less LWP. The seasonal and diurnal variations of cloud LWC and optical depth basically follow the variation of LWP. There are, however, no significant day–night differences and diurnal variations in cloud-droplet effective radius (r_e), number concentration (N_d), and corresponding surface measured cloud condensation nuclei (CCN) number concentration (N_{CCN}) (at supersaturation $S = 0.2\%$). Surface N_{CCN} increases from around sunrise (0300–0600 LT) to late afternoon, which strongly correlates with surface wind speed ($r = 0.76$) from 0300 to 1900 LT. The trend in hourly-mean N_d is consistent with N_{CCN} variation from 0000 to 0900 LT but not for afternoon and evening with an averaged ratio (N_d/N_{CCN}) of 0.35 during the entire study period.

1. Introduction

Dong et al. (2014, hereafter D14) presented a 19-month record of total and single-layered low (<3 km), middle (3–6 km), and high (>6 km) cloud fractions (CFs) and single-layered marine boundary layer (MBL) cloud macrophysical and daytime microphysical properties from ground-based measurements at the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Azores site between June 2009 and December 2010. This record as well as the results from Rémillard et al. (2012) provides the most comprehensive dataset to study the seasonal and diurnal variations of MBL cloud properties, in addition to the vertical distribution of the MBL cloud fraction over the Azores. For the single-layered MBL cloud microphysical properties, D14 did provide the diurnal variations of cloud liquid water path (LWP) and liquid water content (LWC). However, they only presented the daytime LWP, LWC, cloud-droplet effective radius (r_e), number concentration (N_d), and cloud optical depth (τ), as well as surface measured cloud condensation nuclei (CCN) number concentration (N_{CCN}).

In this study, we develop a new algorithm based on the method of Dong and Mace (2003, hereafter DM03) to retrieve the nighttime r_e. Once r_e is known, we can use the same method for daytime retrievals to calculate N_d and τ. The combination of daytime and nighttime results will allow us to investigate the diurnal variations of the MBL cloud microphysical properties over the Azores. Furthermore, the nighttime cloud microphysics retrievals will provide an additional data source to validate the satellite nighttime retrievals over the Azores.

2. Data and method

The datasets used in this study are the same ones used in D14. Since these datasets have been extensively discussed in D14, we will only briefly describe them in this section. The primary dataset used in this study is the 95-GHz W-band ARM Cloud Radar (WACR)

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DOI: 10.1175/JCLI-D-14-00434.1

reflectivity and its derived cloud-top height (Z_{top}) with an uncertainty of 43 m (Mead and Widener 2005) during the deployment of the Atmospheric Radiation Measurement Program (ARM) Mobile Facility (AMF) at the Azores. The WACR has sufficient sensitivity (-50 dBZ at 2 km) to detect MBL small cloud droplets and large light–moderate drizzle drops (Rémillard et al. 2012). The cloud-base height (Z_{base}) can be determined by either micropulse lidar (MPL) or Vaisala ceilometer measurements with uncertainties of 30 and 15 m, respectively (Clothiaux et al. 2000; Rémillard et al. 2012). The cloud physical thickness (ΔH) is simply the difference between Z_{top} and Z_{base}. The cloud LWP is retrieved from the microwave radiometer brightness temperatures measured at 23.8 and 31.4 GHz using a statistical retrieval method with an uncertainty of 20 g m^{-2} for LWP $<$ 200 g m^{-2} and 10% for LWP $>$ 200 g m^{-2} (Liljegren et al. 2001; Dong et al. 2000). The N_{CCN} parameter is calculated using hourly averaged measurements from a Droplet Measurement Technologies (DMT) Model 1 optical particle counter at 0.2% supersaturation by the AMF Mobile Aerosol Observation System at the Azores (Jefferson 2010; Wood et al. 2015).

Following the criteria described in D14, a total 1091 h of daytime and 1445 h of nighttime single-layered and overcast low clouds, and their corresponding surface CCN measurements, have been selected. Five criteria were established for choosing the conditions under which daytime cloud properties can be estimated: (i) only single-layered and overcast low clouds are present as determined from cloud radar/lidar observations, (ii) $Z_{top} <$ 3 km, (iii) 20 $<$ LWP $<$ 700 g m^{-2}, (iv) cosine of solar zenith angle $\mu_0 > 0.1$, and (v) $0.08 <$ solar transmission (γ) < 0.7. The criteria (i)–(iii) for selecting daytime cloudy cases have been used for choosing nighttime cloudy cases in this study.

Following the method of DM03, we develop a new method to retrieve the MBL cloud-droplet effective radius profile $r_e(h)$ in this study, which is independent of solar transmission and can be used during both daytime and nighttime, as well as for multilayered cloud conditions. We derive an empirical relationship between the daytime retrieved $r_e(h)$ and the WACR reflectivity profile from single-layered and overcast MBL clouds as follows:

$$r_e(h) = \frac{\exp(3.912 - 0.5\sigma_X^2)}{N^{0.167}}\exp[0.0384\,\mathrm{dB}Z(h)]$$
$$= a\exp[0.0384\,\mathrm{dB}Z(h)], \quad (1)$$

where $r_e(h)$ represents cloud-droplet effective radius at a given cloud height h and the coefficient a is either 22.7 from November to February or 26.78 for all other months. The layer-mean cloud-droplet effective radius $\overline{r_e}$ is linearly averaged $r_e(h)$ from cloud base to cloud top. Once $\overline{r_e}$ is known, we can use the same method used during the daytime to calculate N_d and τ as follows:

$$N_d = \left[\frac{3\mathrm{LWP}}{4\pi\rho_w r_e^3 \Delta Z}\right]\exp(3\sigma_X^2) \quad \text{and} \quad (2)$$

$$\tau = \frac{3Q_{ext}\mathrm{LWP}}{4\rho_w r_e}. \quad (3)$$

The logarithmic width σ_X is set to 0.38 (Miles et al. 2000), and the broadband shortwave extinction efficiency Q_{ext} is set to 2.1 for $r_e \sim 14\,\mu$m (Dong 1996). Since no concurrent in situ data are available for evaluating the nighttime retrievals over the Azores, the 15%–20% uncertainties for r_e and τ and 30% for N_d estimated from the daytime aircraft in situ measurements during the March 2000 field campaign at the ARM Southern Great Plains (SGP; DM03) should be used as reference. A more detailed explanation of the derivation of (1) is presented in the appendix. Note that the parameter a is derived from the daytime results and then applied to the nighttime clouds. Although the WACR reflectivity is consistent between day and night, the potential differences in meteorological factors between day and night may influence the accuracy of nighttime retrievals. Therefore, the uncertainties of the nighttime retrievals at the Azores should be larger than the suggested ones from the ARM SGP site. However, it is difficult to quantitatively estimate to what extent without aircraft in situ measurements.

3. Results and discussion

To directly compare the daytime and nighttime MBL cloud microphysical properties, we also include the daytime results from D14. Monthly means of both the daytime and nighttime cloud LWP, LWC, r_e, N_d, and τ, as well as surface measured N_{CCN}, are shown in Fig. 1. Their corresponding probability distribution functions (PDFs) and cumulative distribution functions (CDFs) are shown in Fig. 2, and their seasonal and yearly mean, standard deviation, median, and mode values are listed in Table 1. Since these daytime results have been presented and discussed in great detail in D14, we will not discuss these results in this study. Rather, we will compare the nighttime results with their daytime counterparts, and point out their similarities and differences.

As demonstrated in Fig. 1a (Fig. 1b), all nighttime monthly means of LWP exceed their daytime counterparts with an annual mean of 139.6 g m^{-2}, which is ~30.9 g m^{-2} (28.2%) larger than the daytime mean

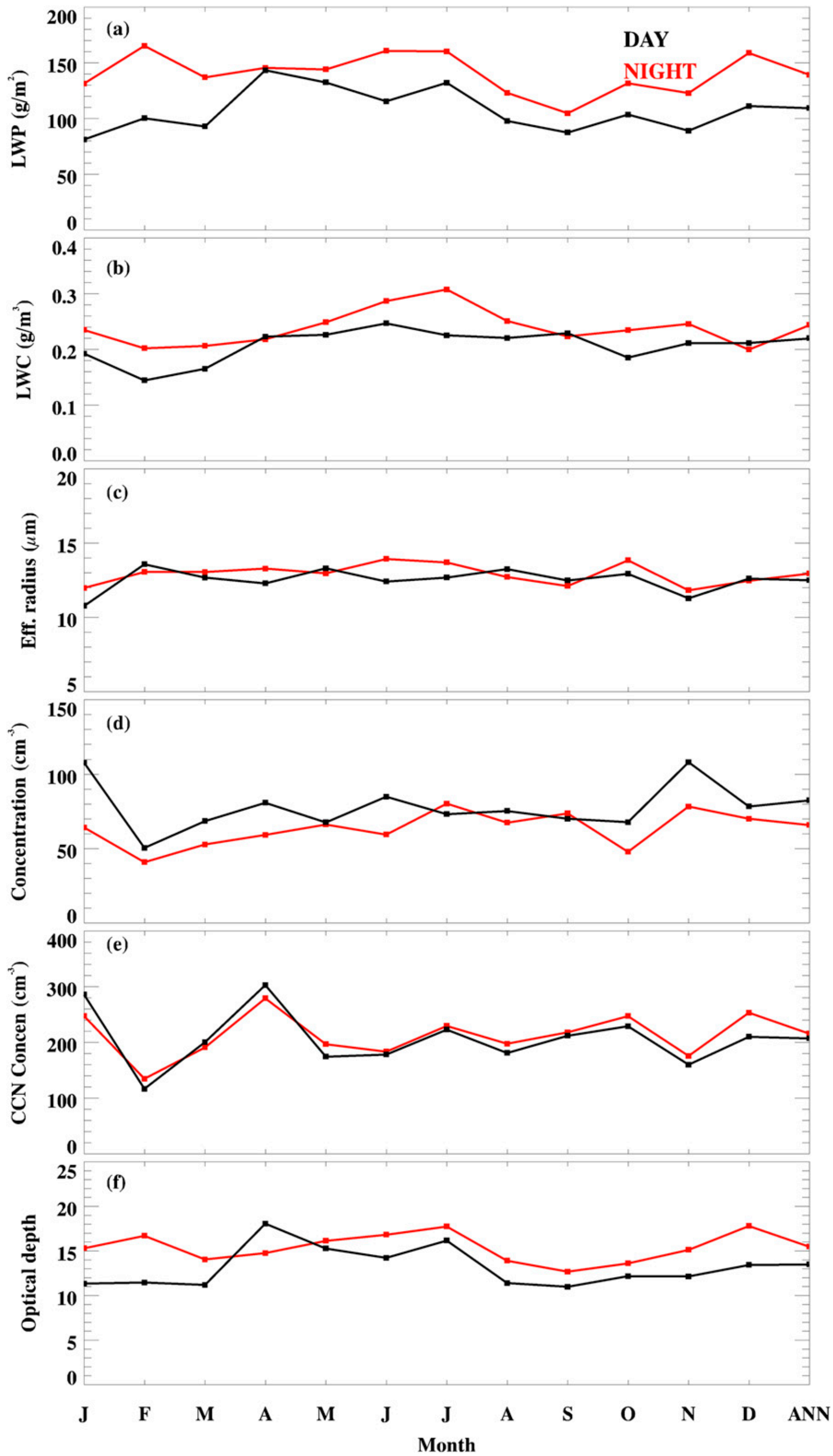

FIG. 1. Monthly-mean daytime (1090 h; black line) and nighttime (1445 h; red line) single-layered MBL cloud microphysical properties derived from 19 months of ARM Azores observations: (a) LWP, (b) LWC, (c) cloud-droplet effective radius r_e, (d) number concentration N_d, (f) optical depth, and (e) surface measured CCN.

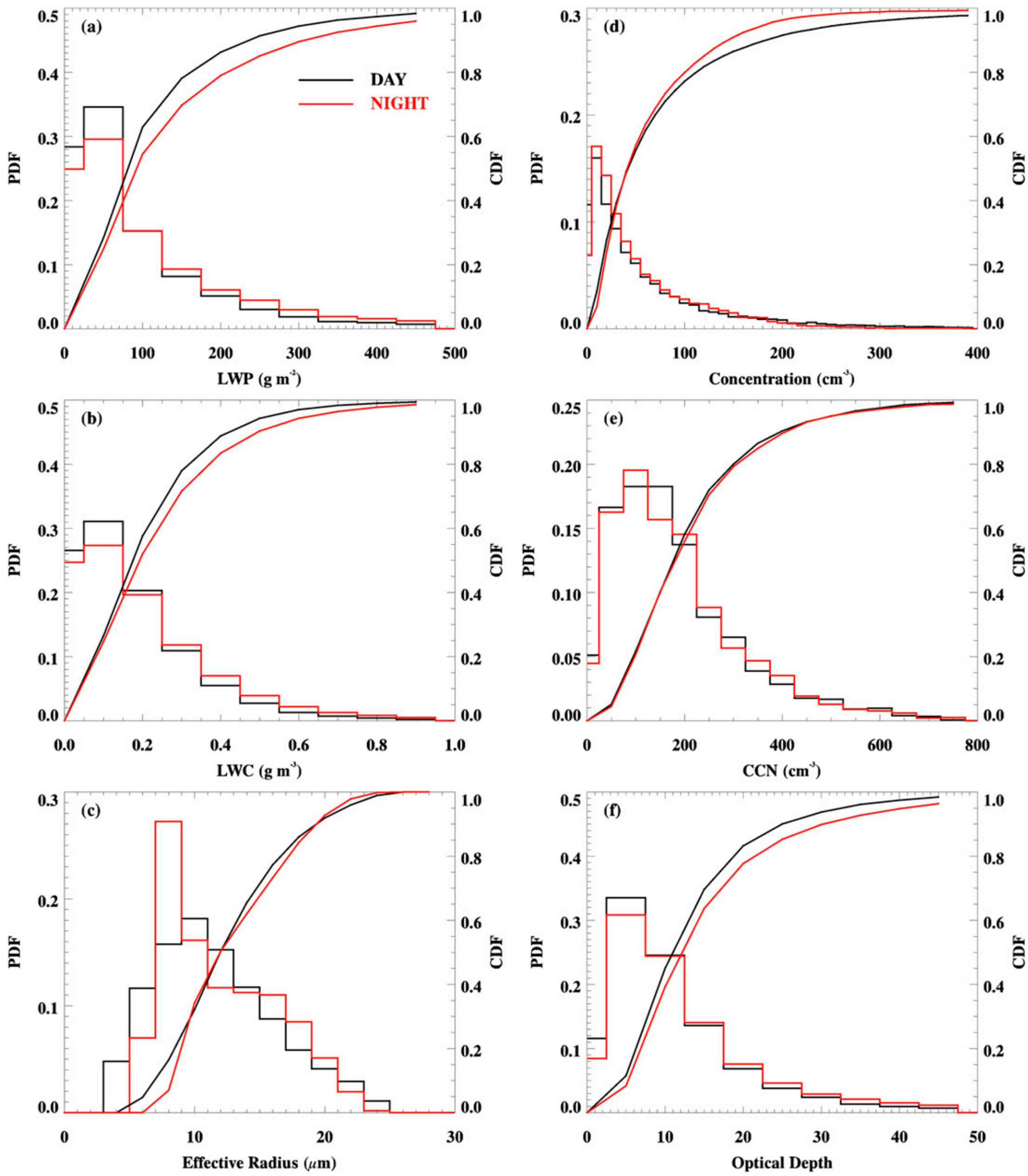

FIG. 2. PDFs and CDFs of single-layered MBL cloud microphysical properties and surface CCN for both daytime (black) and nighttime (red) from all 5-min samples at the ARM Azores site during the 19-month period.

(Table 1). Because the MBL clouds are primarily driven by convective instabilities caused by cloud-top LW radiative cooling, more MBL clouds are well mixed and coupled with the surface during the night (Schwantes 2014; Wood 2005a,b, 2012); thus, its cloud layer is deeper and its LWP is higher. During the day, the cloud layer is warmed by the absorption of solar radiation and partially offsets the cloud-top LW cooling, which makes MBL cloud layer thinner with less LWP. The seasonal variations of cloud LWC and optical depth basically follow the variation of LWP.

The nighttime monthly means of r_e are nearly the same as their daytime counterparts, and both daytime and nighttime r_e values are nearly constant throughout the year. As listed in Table 1, the nighttime annual mean of r_e is 12.9 μm (roughly 0.4 μm larger than its daytime mean) and the nighttime average, standard deviation, median, and mode values are nearly the same as the daytime counterparts with differences less than 2 μm. The nighttime PDF and CDF r_e values are similar to the daytime PDF and CDF trends (Fig. 2c), except for a peak at 8–10 μm. This is consistent with the mode

TABLE 1. Seasonal and yearly averages, standard deviations, medians, and modes of various cloud parameters derived from the 19-month ARM Azores dataset.

	Winter		Spring		Summer		Autumn		Year	
	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
LWP ($g\,m^{-2}$)	99.0	147.4	121.8	138.4	114.4	148.8	93.3	124.6	108.7	139.6
	92.0	144.9	119.9	133.4	96.3	129.6	76.9	115.4	96.0	129.1
	65.7	90.6	75.2	87.5	81.4	100.9	68.7	84.5	75.4	91.6
	25	25	25	75	75	75	75	75	75	75
LWC ($g\,m^{-3}$)	0.16	0.23	0.22	0.24	0.24	0.29	0.21	0.25	0.22	0.26
	0.14	0.21	0.18	0.18	0.17	0.26	0.15	0.19	0.17	0.22
	0.12	0.17	0.17	0.19	0.2	0.23	0.18	0.2	0.18	0.2
	0.05	0.05	0.15	0.16	0.15	0.16	0.15	0.16	0.15	0.16
r_e (μm)	12.4	12.9	12.6	13.1	12.7	13.4	13.6	12.6	12.5	12.9
	5.1	3.9	4.6	4.7	4.2	4.3	4.4	4.1	4.6	4.2
	11.5	12.5	12.0	11.4	11.2	12.4	12.7	11.8	11.9	11.9
	9	9	11	9	11	9	11	9	11	9
N_d (cm^{-3})	75.4	63.4	76.8	64.9	82.5	65.9	89.1	68.1	82.6	66.0
	117.7	125.0	113.4	68.7	137.9	65.9	110.8	103.2	126.2	96.0
	36.3	37.5	40.3	44.8	43.5	44.2	52.4	39.7	44.1	41.0
	5	15	15	15	15	15	15	15	15	15
N_{CCN} (cm^{-3})	265.6	236.9	235.3	231.8	192.5	206.7	196.1	206.6	207.3	215.9
	222.7	198.8	195.9	212.8	109.8	113.6	114.8	125.1	143.8	153.8
	173.9	173.7	162.7	160.8	173.8	193.1	180.4	181.3	175.0	181.3
	125	125	75	75	125	125	175	125	125	125
τ	12.1	16.5	14.9	15.2	14.0	15.0	12.1	16.3	13.5	15.5
	8.4	12.6	12.7	9.3	9.7	12.1	7.3	12.5	9.6	12.1
	10.0	13.1	10.9	9.8	11.4	11.1	10.5	12.7	11.0	11.9
	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5

value of 9 μm in Table 1, while the daytime mode value is 11 μm. Because τ was calculated from (3) (i.e., the ratio of LWP to r_e), the monthly means basically follow the LWP variation since r_e is nearly constant throughout the year. Table 1 shows that the day–night differences in τ are more than 4 during the winter and autumn months while the annual-mean difference is 2.

The nighttime monthly means of N_d fluctuate around an annual mean of 65.9 cm^{-3} with a minimum of 41 cm^{-3} in February and a maximum of 80.3 cm^{-3} in July. Although the nighttime PDF and CDF appear almost identical to their daytime counterparts, nighttime has more low values as shown in Fig. 1 and listed in Table 1. Both the nighttime and daytime monthly means of surface N_{CCN} and the corresponding PDFs and CDFs are nearly identical as well.

Figure 3 shows the hourly means of LWP, LWC, r_e, N_d, N_{CCN}, and τ for the 19-month period. As discussed above and in D14, there are larger nighttime LWP values (140 $g\,m^{-2}$) than daytime (109 $g\,m^{-2}$), suggesting a semidiurnal cycle with maxima occurring at 0500 and 2100 LT, respectively. Because diurnal variations in cloud thickness (D14) and r_e are small, hourly means of LWC and τ are primarily determined by LWP (Figs. 3b,f).

Figure 3e illustrates that the hourly means of N_{CCN} dramatically decrease from midnight (~210 cm^{-3}) to sunrise (176 cm^{-3}) at 0600 LT, immediately increase to 200–210 cm^{-3} during the 0700–1400 LT period, and then rise to ~220 cm^{-3} during late afternoon and night. Therefore, we can conclude that there is an increase in surface CCN from around sunrise (0300–0600 LT) to late afternoon and night at the Azores. By analyzing the hourly means of surface wind speed (10 m; Fig. 3e), the wind speed increases from 4.8 $m\,s^{-1}$ around sunrise to 5.8 $m\,s^{-1}$ at 1400 LT, suggesting a moderate correlation (r = 0.76) between surface N_{CCN} and wind speed. As discussed in Logan et al. (2014), the surface aerosol properties at the Azores are well correlated surface wind speed with greatest contribution from sea salt, but with periodic contribution from continental aerosols.

Although surface CCN measurements are primarily influenced by surface wind speed, precipitation may also be a factor. Hourly means of N_d follow N_{CCN} variations from midnight to 0900 LT, but not for afternoon and evening. The averaged ratio of N_d to N_{CCN} is 0.35 with higher ratios of 0.45 and 0.41 at 0800–0900 and 1800–1900 LT, respectively, and a lower ratio of 0.31 at local noon. This is likely due to a higher frequency of well-mixed MBL episodes during the early morning and late afternoon while more decoupled MBL episodes typically occur near local noon. Thus, further study is necessary.

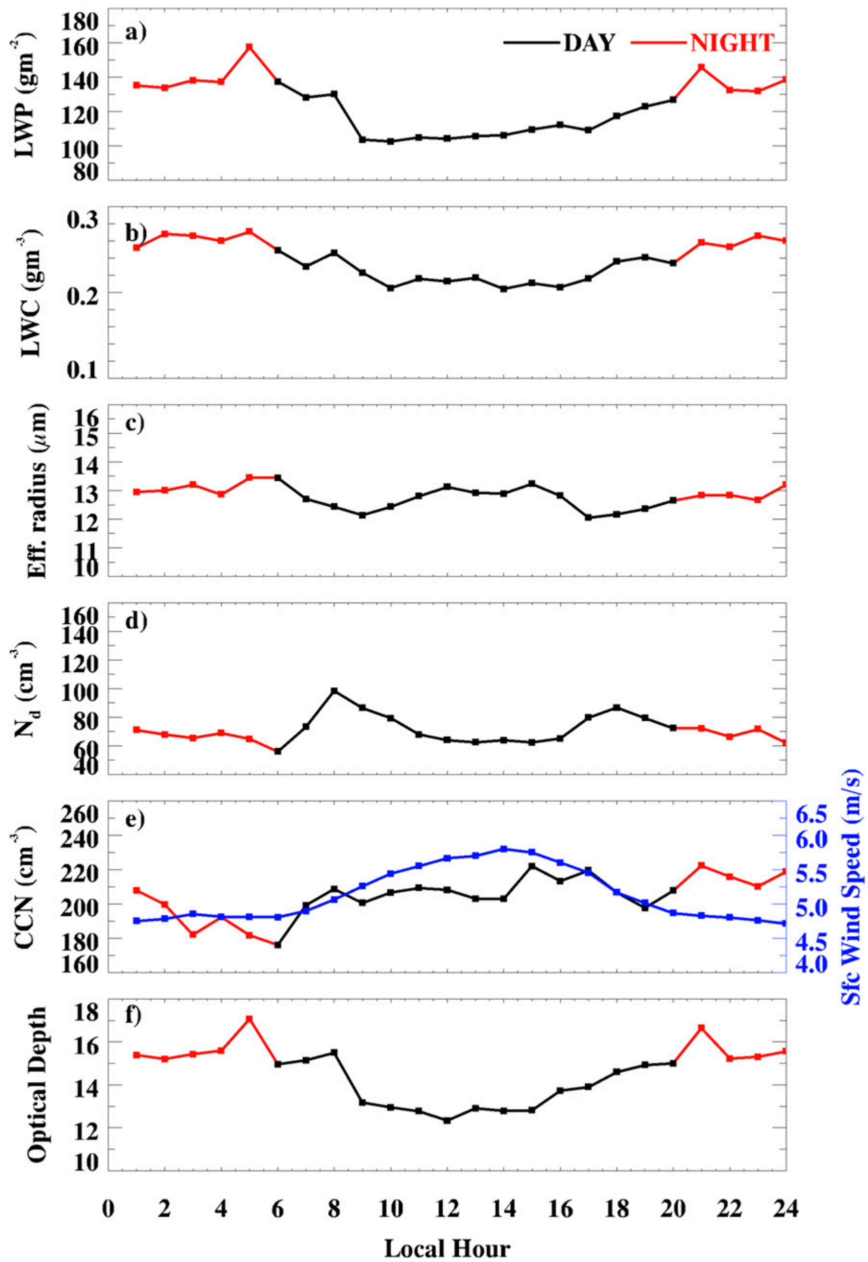

FIG. 3. Hourly means of single-layered MBL cloud microphysical properties from both daytime and nighttime datasets. The daytime and nighttime are shown in each panel with black and red lines, respectively. (e) The blue line is surface wind speed (10 m).

4. Summary and conclusions

This study documents the nighttime MBL cloud microphysical properties, which completes the daytime MBL cloud microphysical properties presented in D14. From the 19-month record of ground-based observations and retrievals, we report the following conclusions:

1) The nighttime monthly means of r_e are nearly identical to the daytime means with an annual difference of 0.4 μm. The day–night differences in monthly-mean N_d and N_{CCN} are very small and their daytime and nighttime PDFs and CDFs are almost the same. The nighttime monthly means of LWP are 30.9 g m^{-2} (28.2%) larger than the daytime means, which results in higher nighttime cloud LWC and optical depth. The PDFs and CDFs of the daytime and nighttime τ values are also very close to each other and very similar to the PDF and CDF of LWPs.

2) Similar to their monthly-mean comparisons, the diurnal variation of r_e is small, while the hourly means of LWC and τ basically follow the diurnal variation of LWP: larger nighttime LWP ($140\,\mathrm{g\,m^{-2}}$) than during the daytime ($109\,\mathrm{g\,m^{-2}}$) with semidiurnal cycle maxima at 0500 LT and 2100 LT, respectively. There is an increase in surface CCN from around sunrise (0300–0600 LT) to late afternoon, which correlates with surface wind speed ($r = 0.76$) from 0300 to 1900 LT. Hourly means of N_d follow N_{CCN} variations well from midnight to 0900 LT, but not for afternoon and evening with an averaged ratio (N_d/N_{CCN}) of 0.35.

Acknowledgments. The data were obtained from the Atmospheric Radiation Measurement Program (ARM), which is sponsored by the U.S. Department of Energy (DOE) Office of Energy Research, Office of Health and Environmental Research, Environmental Sciences Division. This study was primarily supported by the NASA CERES project at University of North Dakota project under Grant NNX13AK29G and by the DOE ASR project at University of North Dakota with Award DE-SC0008468.

APPENDIX

MBL Nighttime Cloud Microphysics Retrieval Algorithm

This study follows the method of DM03 where an empirical relationship is derived between the daytime retrieved cloud-droplet effective radius $r_e(h)$ and the W-band ARM Cloud Radar (WACR; 95 GHz) reflectivity profile from single-layered overcast MBL clouds. This relationship is then applied to calculate r_e values for nighttime and multilayer clouds. The layer-mean cloud-droplet effective radius ($\overline{r_e}$) during daytime was parameterized as a function of cloud LWP, solar transmission (γ), and cosine of solar zenith angle (μ_0) (Dong et al. 1998) and is given by the following expression:

$$\overline{r_e} = -2.07 + 2.49\mathrm{LWP} + 10.25\gamma - 0.25\mu_0 + 20.28\mathrm{LWP}\gamma - 3.14\mathrm{LWP}\mu_0, \qquad \text{(A1)}$$

where the units of $\overline{r_e}$ and LWP are in μm and $100\,\mathrm{g\,m^{-2}}$, respectively. Following the development of DM03 and mathematical derivations and collecting constant terms, we can infer the r_e profile as follows:

$$r_e(h) = \overline{r_e}\left[\frac{\Delta H}{\Delta h}\frac{Z^{1/2}(h)}{\sum_{\mathrm{base}}^{\mathrm{top}} Z^{1/2}(h)}\right]^{1/3}, \qquad \text{(A2)}$$

where ΔH is cloud thickness (m) and Δh is the radar range gate spacing (43 m in this study). In addition, $r_e(h)$ is proportional to both the $\overline{r_e}$ calculated in (A1) and the ratio of the radar reflectivity to the integrated radar reflectivity.

The cloud particle size distribution is assumed as a single mode lognormal size distribution

$$Z(h) = 2^6\,10^{-12} N_d r_e^6(h)\exp(3\sigma_X^3), \qquad \text{(A3)}$$

where σ_X is the logarithmic width of the size distribution, and the units of $r_e(h)$, $Z(h)$, and N_d are μm, $\mathrm{mm^6\,m^{-3}}$, and $\mathrm{cm^{-3}}$, respectively. Taking the $\log_{10}$ of both sides of (A3) and multiplying by 10 to change $Z(h)$ to d$BZ(h)$, we obtain

$$10\log Z(h) = 10\log[2^6 10^{-12} N r_e^6(h)\exp(3\sigma_X^2)], \qquad \text{(A4)}$$

which can be written as

$$\mathrm{d}BZ(h) = 10[1.806 - 12 + 0.4343\ln N + 2.606\ln r_e(h) + 1.303\sigma_X^2]. \qquad \text{(A5)}$$

Solving for $r_e(h)$, we obtain the final expression

$$r_e(h) = \frac{\exp(3.912 - 0.5\sigma_X^2)}{N^{0.167}}\exp[0.0384\,\mathrm{d}BZ(h)] = a\exp[0.0384\,\mathrm{d}BZ(h)]. \qquad \text{(A6)}$$

The coefficient a may not necessarily remain a constant but does depend on the characteristics of the particle size distribution that are driven by such factors as N_{CCN}, updraft velocities, and water vapor supersaturation. Therefore, it is reasonable to assume that the coefficient a will depend on different meteorological factors and air masses. As illustrated in Fig. 1 of D14, low pressure systems are dominant over the Azores during the winter months, which induce anomalous westerly winds that transport moist air mass [relative humidity (RH) ~ 75%–85%] from the North Atlantic to the Azores, thereby producing more multilayered clouds and deep frontal clouds associated with midlatitude cyclones. During the summer and other seasons, persistent high pressure systems give rise to relatively dry conditions

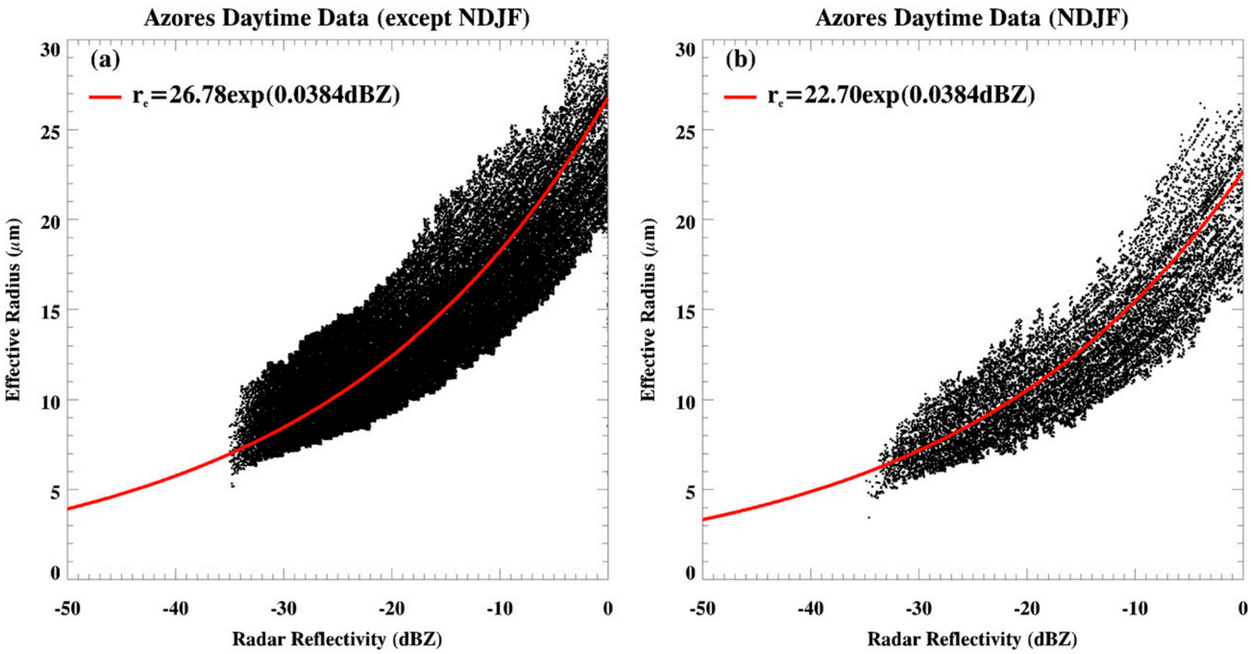

FIG. A1. Empirical relationships between the retrieved daytime cloud-droplet effective radius $r_e(h)$ and the WACR (95 GHz) reflectivity from single-layered and overcast MBL clouds during the 19-month period. The points on the scatterplot are derived from (A2) while the regression lines are plotted using best-fit values for (a) all months except for NDJF, a = 26.78, and (b) NDJF, a = 22.70 in (A6).

(RH ~ 65%–75%) and a transition from an overcast stratocumulus regime to a broken trade cumulus regime. Therefore, we derive two empirical coefficients between $r_e(h)$ and d$BZ(h)$ corresponding to the winter months [November–February (NDJF)] and other months during the 19-month period as shown in Fig. A1 and apply these two relationships to the MBL nighttime r_e retrievals.

The two empirical relationships (a = 22.7 from November to February and a = 26.78 for other months) in Fig. A1 are derived a further explanation. The layer-mean cloud-droplet effect radius $\overline{r_e}$ calculated from (A1) depends on cloud LWP and solar transmission. Although its profile $r_e(h)$ is dependent of radar reflectivity, its values are constrained by $\overline{r_e}$. As demonstrated in Fig. 1c and Table 1, there is no strong seasonal variation in $\overline{r_e}$, while the averaged radar reflectivity from November to February is −13.23 dBZ, which is about 2.72 dBZ higher than the mean of other months. The 2.72 dBZ more from November to February primarily resulted from the higher drizzle frequency (51.2%) from November to February than other months (44.1%) from the selected single-layered overcast MBL clouds in this study. To keep the same $\overline{r_e}$ [or $r_e(h)$] values, the parameter a (=22.7) from November to February must be lower than other months (a = 26.78).

Although the empirical method is the same as DM03, the empirical relationships in this study and DM03 (a = 22.0) are slightly different, which may be attributed to the following reasons: First, the cloud radar wavelength is different (95 GHz at the Azores versus 35 GHz at the ARM SGP). Although we do not compare these two radar reflectivities directly at those two sites, the preliminary comparison during the ARM MAGIC (Marine ARM GPCI Investigation of Clouds) field campaign shows that there is no significant difference between the two radar reflectivity measurements. Second, the low-level clouds at the Azores represent typical MBL clouds, while continental clouds are present at the ARM SGP site. Based on the statistical results from previous studies (e.g., Dong et al. 2005; D14), the averaged daytime $\overline{r_e}$ values are 8.7 and 12.5 μm, respectively, which represent the typical continental and MBL cloud $\overline{r_e}$ values. Other meteorological factors, such as CCN/aerosols and water vapor supersaturation level over these two sites, as well as different synoptic conditions, may also attribute to the difference in parameter a.

REFERENCES

Clothiaux, E. E., T. P. Ackerman, G. G. Mace, K. P. Moran, R. T. Marchand, M. A. Miller, and B. E. Martner, 2000: Objective determination of cloud heights and radar reflectivities using a combination of active remote sensors at the Atmospheric Radiation Measurement Program Cloud and Radiation Test Bed (ARM CART) sites. *J. Appl. Meteor.,* **39,** 645–665, doi:10.1175/1520-0450(2000)039<0645:ODOCHA>2.0.CO;2.

Dong, X., 1996: Microphysical and radiative properties of stratiform clouds deduced from ground-based measurements. Ph.D thesis, Penn State University, 132 pp.

——, and G. G. Mace, 2003: Profiles of low-level stratus cloud microphysics deduced from ground-based measurements. *J. Atmos. Oceanic Technol.,* **20,** 42–53, doi:10.1175/1520-0426(2003)020<0042:POLLSC>2.0.CO;2.

——, T. P. Ackerman, and E. E. Clothiaux, 1998: Parameterizations of microphysical and shortwave radiative properties of boundary layer stratus from ground-based measurements. *J. Geophys. Res.,* **103,** 31 681–31 393, doi:10.1029/1998JD200047.

——, P. Minnis, T. P. Ackerman, E. E. Clothiaux, G. G. Mace, C. N. Long, and J. C. Liljegren, 2000: A 25-month database of stratus cloud properties generated from ground-based measurements at the ARM SGP site. *J. Geophys. Res.,* **105,** 4529–4538, doi:10.1029/1999JD901159.

——, ——, and B. Xi, 2005: A climatology of midlatitude continental clouds from the ARM SGP Central Facility. Part I: Low-level cloud macrophysical, microphysical and radiative properties. *J. Climate,* **18,** 1391–1410, doi:10.1175/JCLI3342.1.

——, B. Xi, A. Kennedy, P. Minnis, and R. Wood, 2014: A 19-month record of marine aerosol-cloud-radiation properties derived from DOE ARM AMF deployment at the Azores: Part I: Cloud fraction and single-layered MBL cloud properties. *J. Climate,* **27,** 3665–3682, doi:10.1175/JCLI-D-13-00553.1.

Jefferson, A., 2010: Empirical estimates of CCN from aerosol optical properties at four remote sites. *Atmos. Chem. Phys.,* **10,** 6855–6861, doi:10.5194/acp-10-6855-2010.

Liljegren, J. C., E. E. Clothiaux, G. G. Mace, S. Kato, and X. Dong, 2001: A new retrieval for cloud liquid water path using a ground-based microwave radiometer and measurements of cloud temperature. *J. Geophys. Res.,* **106,** 14 485–14 500, doi:10.1029/2000JD900817.

Logan, T., B. Xi, and X. Dong, 2014: Aerosol properties and their influences on marineboundary layer cloud condensation nuclei at the ARM Mobile Facility over the Azores. *J. Geophys. Res.,* **119,** 4859–4872, doi:10.1002/2013JD021288.

Mead, J. B., and K. B. Widener, 2005: W-band ARM cloud radar. Preprints, *32nd Int. Conf. on Radar Meteorology,* Albuquerque, NM, Amer. Meteor. Soc., P1R.3. [Available online at http://ams.confex.com/ams/pdfpapers/95978.pdf.]

Miles, N. L., J. Verlinde, and E. E. Clothiaux, 2000: Cloud-droplet size distributions in low-level stratiform clouds. *J. Atmos. Sci.,* **57,** 295–311, doi:10.1175/1520-0469(2000)057<0295:CDSDIL>2.0.CO;2.

Rémillard, J., P. Kollias, E. Luke, and R. Wood, 2012: Marine boundary layer clouds observations in the Azores. *J. Climate,* **25,** 7381–7398, doi:10.1175/JCLI-D-11-00610.1.

Schwantes, A., 2014: Investigation of stratocumulus macro- and micro-physical properties under coupled and decoupled boundary layer regimes over the ARM Azores site. M.S. thesis, Dept. of Atmospheric Sciences, University of North Dakota, 84 pp.

Wood, R., 2005a: Drizzle in stratiform boundary layer clouds. Part I: Vertical and horizontal structure. *J. Atmos. Sci.,* **62,** 3011–3033, doi:10.1175/JAS3529.1.

——, 2005b: Drizzle in stratiform boundary layer clouds. Part II: Microphysical aspects. *J. Atmos. Sci.,* **62,** 3034–3050, doi:10.1175/JAS3530.1.

——, 2012: Review stratocumulus clouds. *Mon. Wea. Rev.,* **140,** 2373–2416, doi:10.1175/MWR-D-11-00121.1.

——, and Coauthors, 2015: Clouds, aerosol, and precipitation in the marine boundary layer: An ARM Mobile Facility deployment. *Bull. Amer. Meteor. Soc.,* in press.