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# NOTES AND CORRESPONDENCE

## Comments on "Seasonal Variation of the Physical Properties of Marine Boundary Layer Clouds off the California Coast"

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By combining data from multiple sources, Lin et al. (2009, hereafter L09) have lately performed a rather comprehensive comparison of the seasonal differences in several macrophysical properties of marine boundary layer (MBL) clouds observed off the California coast [e.g., cloud fraction, liquid water path (LWP), cloud-top and cloud-base heights, cloud thickness $H$, inversion strength, lifted condensation level, and the degree of decoupling]. They found that most differences between the summer [June–August (JJA)] and winter [December–February (DJF)] seasons can be explained by the characteristics of lower-tropospheric stability (LTS; Slingo 1980; Klein 1997) and the deepening–warming–decoupling hypothesis proposed in Bretherton and Wyant (1997). Although this work certainly constitutes an excellent contribution to the understanding and parameterization of MBL clouds by considering multiple variables together, it is primarily confined to macrophysical properties, only with a brief mentioning of the cloud droplet effective radius. In this paper, I will demonstrate that credible microphysical information can, in fact, be inferred from the same datasets provided in L09, which further suggests at least equally strong summer–winter differences in microphysical properties and a plausible microphysical effect. Note that here "microphysical" is used in a general sense to denote any variables that can be derived from a local cloud droplet size distribution without involving cloud geometrical properties (e.g., liquid water content, droplet concentration, and effective radius).

The first microphysical quantity is the cloud-layer mean liquid water content $L$. In their Figs. 5b and 5f, L09 compared LWP and $H$ observed during the summer and winter seasons, and they concluded that the summer–winter difference in LWP is much larger than that in the cloud thickness. Because LWP can be regarded as a product of $H$ and $L$,

$$\mathrm{LWP} = HL, \tag{1}$$

$L$ is readily obtained from LWP and $H$ by use of the variant of (1): $L = \mathrm{LWP}/H$. Accordingly, a large summer–winter difference in $L$ is anticipated from the distinct contrast between the summer–winter differences in LWP and $H$. This point can be clearly seen in Fig. 1a, which contrasts the variations of the summertime and wintertime $L$ with the distance from the California coast. Figures 1b and 1c are a reproduction of Figs. 5b and 5e in L09 for the convenience of comparison. The higher summertime $L$ is likely related to the larger $dq_{\mathrm{sat}}/dz$ associated with the corresponding lower cloud-base height as reported in L09; $q_{\mathrm{sat}}$ is the saturation mixing ratio, and adiabatic liquid water content is approximately proportional to $dq_{\mathrm{sat}}/dz$ at a given height $z$ (Albrecht et al. 1990). In addition to the expected summer–winter difference, $L$ also exhibits a unique variation with the distance from the coast: in wintertime, the farther away from the California coast, the higher the $L$ value; in summertime, the opposite appears true. But, the physics behind the converging trend of the summertime and wintertime $L$ from the coast to the ocean is elusive at present.

The second microphysical quantity is the cloud droplet number concentration $N$. Without providing a detailed analysis, L09 mentioned that, "Retrievals from (Clouds and the Earth's Radiant Energy System–Moderate Resolution Imaging Spectroradiometer) CERES–MODIS, however, have shown that the effective radius is smaller in JJA than in DJF." Crucial information on $N$ can be

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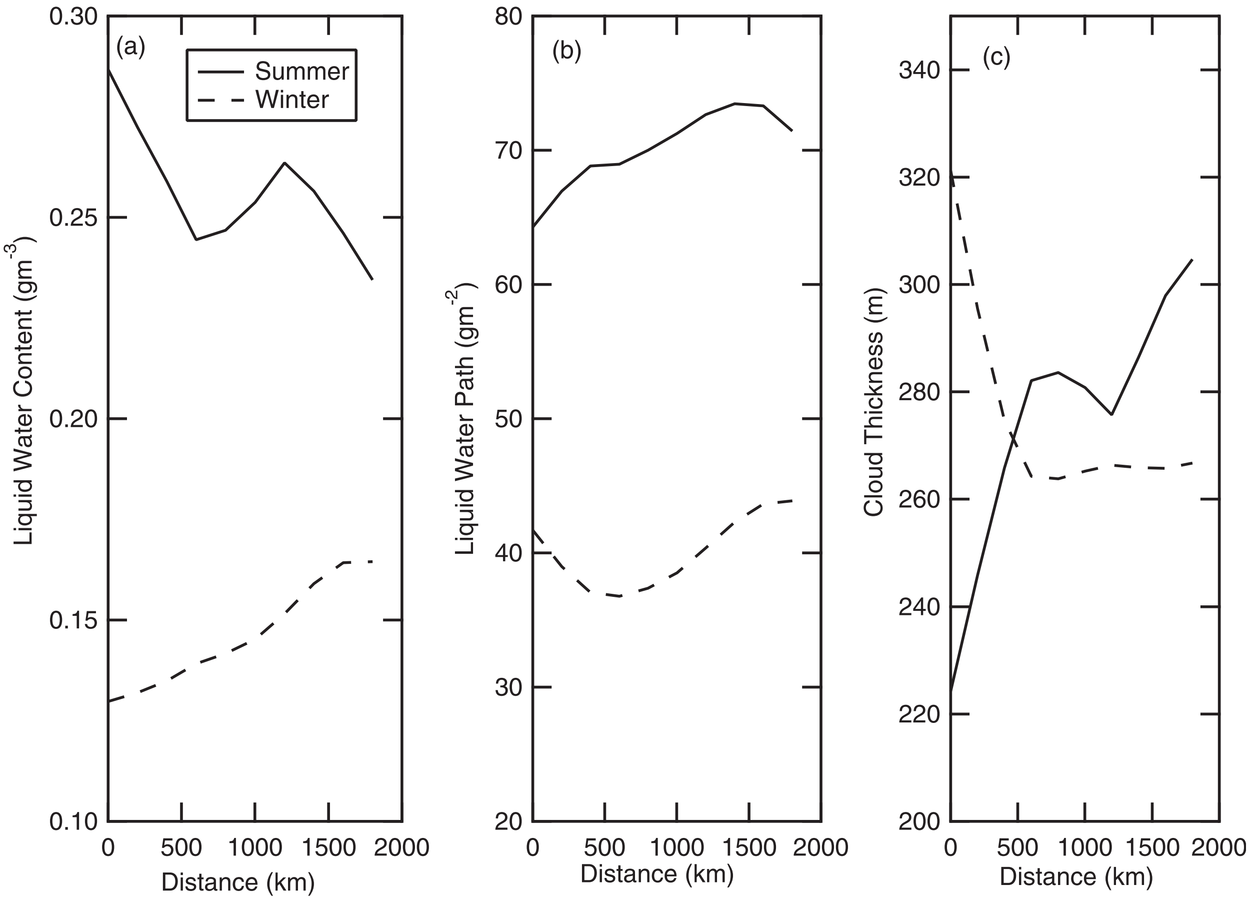


FIG. 1. Variation of the (a) liquid water content, (b) LWP, and (c) cloud thickness with the distance off the California coast into the ocean. (b),(c) are adapted from Figs. 5b and 5e of L09, respectively, for the purpose of comparison; (a) is derived from the data of LWP and cloud thickness according to the method detailed in this comment.

further inferred from the results of $L$ and effective radius $r_e$ by examining the relationship between the three microphysical variables. Without loss of generality, $r_e$ is related to $L$ and $N$ by the general power–law relationship (Liu and Hallett 1997; Liu and Daum 2000; Liu et al. 2008):

$$r_e = a_e\left(\frac{L}{N}\right)^{b_e}, \tag{2}$$

where $a_e$ and $b_e$ are two empirical coefficients that have been often assumed as constant, especially in remote sensing of cloud properties (e.g., Han et al. 1998; Boers et al. 2006).

With the data on $L$ and $r_e$, $N$ can be readily estimated using (2) with a given pair of $a_e$ and $b_e$ [see more discussion on the two coefficients in Boers et al. (2006) and Liu et al. (2008)]. In fact, a few studies have attempted to retrieve $N$ from satellite measurements based on equations similar to (2) (Han et al. 1998; Szczodrak et al. 2001; Schuller et al. 2003; Boers et al. 2006). Even without knowing the specific values of $N$, some salient feature of the summer–winter difference in $N$ can be deduced by mathematical analysis of (2). Differentiation of (2) yields the equation that describes the fractional differences in $N$, $L$, and effective radius:

$$\frac{\Delta N}{N} = \frac{\Delta L}{L} - \frac{1}{b_e}\frac{\Delta r_e}{r_e} + \frac{1}{b_e}\frac{\Delta a_e}{a_e}, \tag{3a}$$

where $\Delta$ denotes the difference between the summer and winter clouds. To the first order approximation, it can be assumed that the two coefficients $a_e$ and $b_e$ are same during the summer and winter seasons. Under this assumption, (3a) is simplified as

$$\frac{\Delta N}{N} = \frac{\Delta L}{L} - \frac{1}{b_e}\frac{\Delta r_e}{r_e}. \tag{3b}$$

Equation (3b) clearly reveals that when the summertime $r_e$ is smaller than that of the winter cloud, or $\Delta r_e < 0$, the difference in $L$ not only means a difference in $N$ but more interesting is that the summer–winter difference in $N$ is larger than that in $L$, or

$$\frac{\Delta N}{N} > \frac{\Delta L}{L}. \tag{3c}$$

More specific information on the relationship between the relative differences can be obtained by examining two special values of $b_e$. The first case is the commonly used one of $b_e = 1/3$. For this case, the relative summer–winter difference in $N$ is given by

$$\frac{\Delta N}{N} = \frac{\Delta L}{L} - 3\frac{\Delta r_e}{r_e}. \tag{4a}$$

Despite its popularity, $b_e = 1/3$ holds only if the spectral shape of the cloud droplet size distribution remains unchanged when $N$ and $L$ vary. However, recent studies have shown that some physical processes simultaneously affect $L$, $N$, and the spectral shape (Liu and Daum 2002; Yum and Hudson 2005; Liu et al. 2006; Peng et al. 2007; Hsieh et al. 2009). By analyzing a collection of cloud data obtained during several field campaigns, Liu et al. (2008) obtained $b_e = 0.19$, smaller than the commonly used $b_e = 1/3$ because of concurrent increases of $N$ and relative dispersion of the cloud droplet size distribution and spectral narrowing of adiabatic condensational growth. For the case of $b_e = 0.19$, we have

$$\frac{\Delta N}{N} = \frac{\Delta L}{L} - 5.26\frac{\Delta r_e}{r_e}. \tag{4b}$$

Comparison of (4b) with (4a) shows that consideration of the spectral shape effect results in an even larger difference in $N$.

The third microphysical quantity is the drizzle rate, which can be examined using the diagnostic relationship between cloud-base drizzle rate $P$, LWP, and $N$ found from surface-based remote sensing (Wood et al. 2008):

$$P = 0.37\left(\frac{\mathrm{LWP}}{N}\right)^{1.75}, \tag{5}$$

where $P$ is in mm day$^{-1}$, LWP is in g m$^{-2}$, and $N$ is in cm$^{-3}$. A combination of (1), (2), and (5) leads to

$$P = 0.37\left(\frac{\mathrm{LWP}}{N}\right)^{1.75} = 0.37a_e^{-1.75/b_e}r_e^{1.75/b_e}H^{1.75}. \tag{6}$$

Evidently, $P$ can be estimated from LWP and $N$ using the first identity, or from $r_e$ and $H$ using the second identity. Using the second identity one also needs to assume the values of $a_e$ and $b_e$. Again, useful information can be inferred from what L09 provided without knowing the concrete values of $N$ and $r_e$. L09 reported that compared to the winter cloud, the summertime cloud has a smaller $r_e$ but approximately the same $H$. Together with (6), this finding suggests that the summertime cloud has a smaller drizzle rate than the wintertime cloud.

It is interesting to note that the totality of the microphysical summer–winter differences inferred from what L09 provided—the summertime cloud has a higher $L$ and $N$ but lower $r_e$ and $P$—resembles the majority of the microphysical differences between closed and open convective cells in MBL clouds, and/or between the so-called pockets of open cells (POCs) and their surrounding solid clouds. In search for understanding cellular cloud structure, there have been increasing number of studies on the connection between the cellular structure and microphysics via drizzles (e.g., Stevens et al. 2005; Petters et al. 2006; Sharon et al. 2006; Wood et al. 2008). These studies have reported compelling observational evidence that the microphysical characteristics in solid decks or closed cells differ substantially from those of POCs or open cells, with open cells or POCs being associated with lower $N$ but larger $r_e$ and $P$. Numerical simulations (Savic-Jovcic and Stevens 2008; Xue et al. 2008; Wang and Feingold 2009) have confirmed these observations and further suggested that enhanced precipitation plays a critical role in the formation and evolution of open cells, and evaporation of raindrops generate a dynamic response that promotes, organizes, and sustains open-cell structures. Lower cloud condensation nuclei (CCN)/aerosol concentrations have also been found to be associated with open cells and POCs, implying potential aerosol influences. Although it cannot be conclusive without supporting CCN/aerosol data, the remarkable microphysical similarity between the summer–winter microphysical differences inferred from L09 and those between the closed (solid decks) and open cells (POCs) is certainly indicative of a microphysical mechanism for winter clouds that is in action for open cells and POCs. The summer–winter differences in the microphysical properties are also consistent with the dominant mechanisms proposed for aerosol indirect effects: an increase in aerosol loading leads to a higher $N$ but a smaller effective radius (Twomey 1967), and less drizzle but higher $L$ and LWP (Albrecht 1989).

L09 pointed out that the seasonal variations of the macrophysical cloud properties from summer to winter resemble the downstream stratocumulus-to-cumulus transition of MBL clouds, and that the "deepening–warming–decoupling" mechanism proposed by Bretherton and Wyant (1997) can explain the summer–winter cloud differences when the warming of the sea surface temperature is relative to the temperature of the free troposphere.

TABLE 1. Summary of quantitative summer–winter differences in main properties.

| Property | Summertime | Wintertime | Relative diff (%) |
|---|---|---|---|
| Cloud fraction (%) | Larger, 74.77 | Smaller, 57.34 | 23 |
| LWP | Higher, 70.12 | Lower, 40.06 | 43 |
| Cloud thickness (m) | Similar, 280 | Similar, 270 | 4 |
| Cloud-base height (m) | Lower, 430 | Higher, 950 | −121 |
| Cloud-top height (m) | Lower, 710 | Higher, 1220 | −72 |
| Lower-tropospheric stability (°C) | Stronger, 22 | Weaker, 17 | 23 |
| Inversion strength (°C) | Stronger, 7.4 | Weaker, 6.0 | 19 |
| Lifted condensation level (m) | Lower, 410 | Higher, 470 | −15 |
| Surface latent heat flux (W $m^{-2}$) | Smaller, 71 | Larger, 87 | −23 |
| Sea surface temperature (°C) | Higher, 19 | Lower, 14 | 26 |
| Liquid water content (g $m^{-3}$) | Larger, 0.26 | Smaller, 0.15 | 42 |
| Droplet concentration ($cm^{-3}$) | Larger, 53 | Smaller, 15 | 72 |
| Effective radius ($\mu$m) | Smaller, 11.4 | Larger, 14.6 | −28 |
| Drizzle rate | Smaller, 0.67 | Larger, 2.38 | −255 |

Together with the plausible microphysical mechanism, the question arises as to which mechanism—the macrophysical discussed in L09 or the microphysical mechanism discussed here—is more important in determining the seasonal differences. Of course, macrophysics and microphysics are likely the two sides of the same coin, and the seasonal differences may stem from interwoven actions of both macrophysical and microphysical mechanisms via multiscale interactions/feedbacks.

Responding to my original comment, L09 have performed the microphysical analyses suggested earlier, and their results largely support the expected microphysical differences outlined earlier (see their response for details). Deeper insights can be obtained by examining their new results. Table 1 juxtaposes the main macrophysical and microphysical quantities for the summertime and wintertime clouds and compared their relative differences defined as (summertime − wintertime)/summertime. The six variables that have the largest relative summer–winter differences are $P$ (−255%), cloud-base height (−121%), $N$ (72%), cloud-top height (−72%), $L$ (42%), and $r_e$ (−28%). Note that the difference in liquid water path (43%) is not listed because it primarily reflects the difference in liquid water content, as the wintertime and summertime clouds have similar cloud thickness. These composite results seem to support joint roles of macrophysics and microphysics via drizzles, as a higher cloud base in the winter cloud tends to associate with lower droplet concentration and liquid water content. An analytical steady-state formulation also confirms the essential role of $N$ in determining $P$ (R. Wood 2009, personal communication).

The new results also indicate that like $L$, the changes of $N$, $r_e$, and $P$ with the distances from the California coast all exhibit a converging trend. Figure 2 further compares the relative summer–winter differences in the four microphysical properties as a function of the distance away from the California coast. As for the mean discussed earlier, Fig. 2 shows that $P$ and $N$ have the largest seasonal differences from the coast to the ocean, providing additional support for the crucial role of $N$ in determining $P$. However, it has proven difficult to tell whether a smaller $N$ (aerosols) causes a higher $P$ first or if it is caused by a larger $P$ because of the positive feedback loop between $N$ and $P$. The converging behaviors of the microphysical differences shed further insight on this issue: The gradual decreases of all the microphysical differences with increasing distances from the California coast suggest the importance of coastal proximity and thus aerosols in shaping the summer–winter differences.

It has been long recognized that MBL clouds are highly coupled systems with complex interactions between

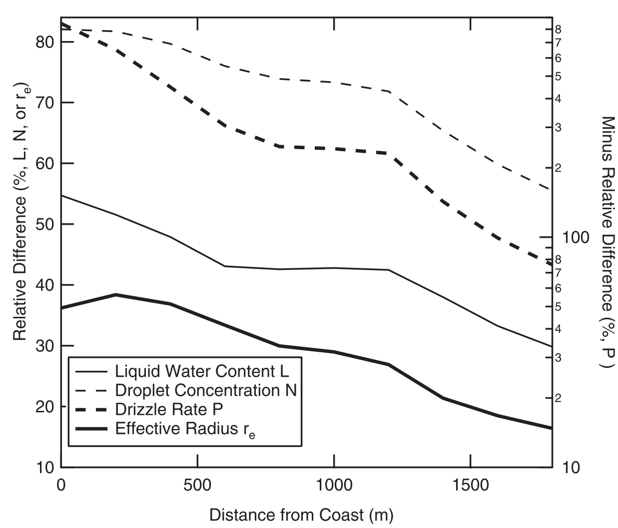


FIG. 2. Change of the relative differences in the microphysical properties with the distance off the California coast into the ocean. Note (1) the minus relative difference is shown for $r_e$; also noted is the different scale used for the drizzle rate.

thermodynamics, dynamics, radiation, and microphysics, and growing efforts have been recently devoted to understanding the coworkings of macrophysics and microphysics (Kubar et al. 2009; Wood et al. 2009). Nevertheless, a full theoretical framework for such highly coupled systems is still posing a challenge. This is especially true for developing an adequate representation of MBL clouds in climate models where cloud macrophysics (e.g., cloud fraction) and microphysics (e.g., aerosol effects) are often treated separately. More comprehensive analyses and idealized numerical simulations should be essential for addressing these intriguing issues.

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