CCN and Vertical Velocity Influences on Droplet Concentrations and Supersaturations in Clean and Polluted Stratus Clouds

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ABSTRACT

Cloud microphysics and cloud condensation nuclei (CCN) measurements from two marine stratus cloud projects are presented and analyzed. Results show that the increase of cloud droplet concentrations \(N_c\) with CCN concentrations \(N_{CCN}\) rolls off for \(N_{CCN}\) at 1% supersaturation \((S)N_{1\%}\) above 400 cm\(^{-3}\). Moreover, at such high concentrations \(N_c\) was not so well correlated with \(N_{CCN}\) but tended to be more closely related to vertical velocity \(W\) or variations of \(W (\sigma_w)\). This changeover from predominately \(N_c\) dependence on \(N_{CCN}\) to \(N_c\) dependence on \(W\) or \(\sigma_w\) variations is due to the higher slope \(k\) of CCN spectra at lower \(S\), which is made more relevant by the lower cloud \(S\) that is forced by higher \(N_{CCN}\). Higher \(k\) makes greater influence of \(W\) or \(\sigma_w\) variations than \(N_{CCN}\) variations on \(N_c\). This changeover at high \(N_{CCN}\) thus seems to limit the indirect aerosol effect (IAE).

On the other hand, in clean-air stratus cloud \(S\) often exceeded 1% and decreased to slightly less than 0.1% in polluted conditions. This means that smaller CCN [those with higher critical \(S\) (\(S_c\)], which are generally more numerous than larger CCN (lower \(S_c\)], are capable of producing stratus cloud droplets, especially when they are advected into clean marine air masses where they can induce IAE. Positive correlations between turbulence \(\sigma_w\) and \(N_{CCN}\) are attributed to greater differential latent heat exchange of smaller more numerous cloud droplets that evaporate more readily. Such apparent CCN influences on cloud dynamics tend to support trends that oppose conventional IAE, that is, less rather than greater cloudiness in polluted environments.

1. Introduction

Low stratus clouds that predominate the east sides of oceans provide a majority of the indirect aerosol effect (IAE; Warren et al. 1988; Platnick and Twomey 1994; Kogan et al. 1996), which remains the largest climate uncertainty (Alley et al. 2007). The high radiative temperatures and large albedo contrasts with the underlying ocean provide substantial global cooling that can be increased by the advection and injection of anthropogenic cloud condensation nuclei (CCN), which increase cloud droplet concentrations \(N_c\) (albedo; first IAE; Twomey 1977a) and decrease droplet sizes (lifetime; second IAE; Albrecht 1989). CCN concentrations \((N_{CCN})\) or more specifically CCN spectra \((N_{CCN active}\) at various levels of supersaturation \(S\) and vertical velocity \(W\) at cloud base are the main determinants of \(N_c\) and the subsequent spectra of cloud droplets. Hudson et al. (2010a, hereafter H10) broke the conventional wisdom of maximum \(S < 0.3\%\) (100.3% RH) in stratus clouds (Hudson 1983; Hoppel et al. 1986; Leaitch et al. 1996; Roberts et al. 2006; Hegg et al. 2009) by comparing below-cloud CCN spectra with nearby \(N_c\) during the Physics of Stratocumulus Tops (POST) project (Carman et al. 2012).

Here we present further analysis of POST along with measurements and analysis of a complementary field project, the Marine Stratus/Stratocumulus Experiment (MASE) of July 2005 (Wang et al. 2009). Although both of these aircraft research projects were done in the same area off the central California (CA) coast (Tables 1–2) in summertime stratus clouds, there were several important contrasts between them (Table 3). The differences were greatly due to the shorter period of the MASE data that are presented here from 9 flights on 9 days over 11 days (15–25 July 2005) whereas POST data are presented from 13 flights on 13 days over 29 days (18 July–15 August 2008). The foremost differences were higher \(N_{CCN}\) (Table 3, columns 2–7, Fig. 1a) and \(N_c\) (Table 3, columns 8–10) and smaller droplets (Table 3, columns 11–13 and Fig. 2) in MASE. The longer time period and greater number of flights in POST contributed to the
greater variety of aerosol (Table 3, columns 3–4 and 6–7), $N_c$ (Table 3, columns 9–10) and droplet mean diameters (MD; Table 3, columns 12–13) during POST. For all of these variables the maximum values of the two projects are similar but the minimal values of the two projects differ by a factor of 2 to an order of magnitude. One important aspect that could have been related to these microphysical differences was the lower cloud tops and especially lower cloud bases during MASE (Table 2, column 6), which made it difficult to obtain below-cloud CCN measurements. Higher cloud bases and a slower airplane (Twin Otter compared to Gulfstream 1; Table 2, column 2) allowed more extensive below-cloud measurements during POST (Table 2, columns 9–10). The persistent aerosol layer above CA stratus (e.g., Hudson and Frisbie 1991) was often absent during POST (H10) but always present during the MASE flights considered here. Here we take the opportunity to advance understanding of IAE by comparing and contrasting aerosol–cloud relationships between these two field projects done in clouds that are the most relevant to IAE.

2. Measurements

As with H10 all POST measurements were made on board the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter airplane based at Marina, California, just north of Monterey. Cloud and drizzle droplet probes and $W$ measurements from this airplane have been presented by Conant et al. (2004), Lu et al. (2007, 2008, 2009, 2012), Small et al. (2009), and H10. Cloud measurements were made by the cloud, aerosol, and precipitation spectrometer (CAPS) of Droplet Measurements Technologies of Boulder, Colorado (Baumgardner et al. 2001). The two components of CAPS used in this study are the cloud and aerosol spectrometer (CAS) for cloud droplets between 0.58 and 51-$\mu$m diameter and the cloud imaging probe (CIP) for drizzle drops between 50- and 1500-$\mu$m diameter. A five-hole gust probe on the radome of the airplane and a pitot-static pressure tube with a GPS-corrected C-MIGITS III using the technique of Lenschow (1986) (Lenschow and Spyers-Duran 1989) as described by Khelif et al. (1999, 2005) determined $W$. The $W$ measurements from this aircraft have been presented by Lu et al. (2007, 2008, 2009, 2012).

All measurements during MASE were made on the Department of Energy Gulfstream 1 (G1) airplane, which was based in Sacramento, California, during MASE. A similar CAPS probe and a slightly different five-hole gust probe (Brown et al. 1983; Chan et al. 1998) were used on the G1. During one of the MASE flights the $W$ measurements were favorably compared with model simulations (Guo et al. 2008).

CCN spectra in both projects were measured with the Desert Research Institute (DRI) CCN spectrometers (Hudson 1989), which have been used and reported from numerous aircraft field experiments (Hudson and Yum 2002, 2001; Yum and Hudson 2004; Hudson and Mishra 2007; Hudson and Noble 2009; Hudson et al. 2009, 2010b, 2012). In both the POST and MASE projects this instrument was calibrated at least once during each flight. During MASE there were two DRI CCN spectrometers operating over slightly different $S$ ranges and there was good agreement between the two instruments in the overlapping $S$ range (not shown).

Flight durations in each project were $\sim$4 h. With the exception of Fig. 3a, all cloud data are from 1-s averages.
during horizontal flight at constant altitudes. As in previous publications by the authors, cloud data were restricted to only those seconds with cloud probe (here the CAS) liquid water content (LWC) greater than 0.1 g m\(^{-3}\). Mean values of all of these 1-s values in each cloud pass are used in this analysis. As described in section 6 of the 28 POST clouds and 12 of the 38

TABLE 3. Project, mean and std dev of \(N_{c0.1\%}\), minimum \(N_{c0.1\%}\), maximum \(N_{c0.1\%}\), mean and std dev of \(N_{c1\%}\), minimum \(N_{c1\%}\), maximum \(N_{c1\%}\), mean and std dev of slope of CCN spectra at \(N_{CCN}=S\), \(k_{@N_{c}}\), mean and std dev of droplet mean diameter (MD), minimum MD, maximum MD, activation ratio, and mean and std dev of slope of CCN spectra at \(N_{CCN}=S\), \(k_{@N_{c}}\).

<table>
<thead>
<tr>
<th>Project</th>
<th>(N_{c0.1%}) (cm(^{-3}))</th>
<th>(N_{c0.1%}) min (cm(^{-3}))</th>
<th>(N_{c0.1%}) max (cm(^{-3}))</th>
<th>(N_{c1%}) (cm(^{-3}))</th>
<th>(N_{c1%}) min (cm(^{-3}))</th>
<th>(N_{c1%}) max (cm(^{-3}))</th>
<th>MD ((\mu)m)</th>
<th>MD min ((\mu)m)</th>
<th>MD max ((\mu)m)</th>
<th>(k_{@N_{c}})</th>
<th>Activation Ratio</th>
<th>Slope of CCN spectra at (N_{CCN}=S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>POST</td>
<td>634 ± 132</td>
<td>381</td>
<td>914</td>
<td>235</td>
<td>240</td>
<td>280 ± 194</td>
<td>76</td>
<td>63</td>
<td>194</td>
<td>132</td>
<td>381</td>
<td>914</td>
</tr>
<tr>
<td>MASE</td>
<td>132 ± 381</td>
<td>84</td>
<td>45</td>
<td>104</td>
<td>103</td>
<td>52 ± 76</td>
<td>6</td>
<td>76</td>
<td>235</td>
<td>48</td>
<td>381</td>
<td>914</td>
</tr>
</tbody>
</table>

FIG. 1. (a) Mean POST and MASE CCN spectra. The most polluted POST flight (18 Jul) is plotted separately. (b) The \(k\) of (a) are shown.

FIG. 2. Mean differential droplet spectra of all of the horizontal cloud passes analyzed in each project.
MASE clouds were divided so that 34 POST clouds and 50 MASE clouds were considered throughout this analysis; Table 1 displays differences before and after these splits of some of the cloud passes.

All CCN measurements were made in horizontal flight legs below cloud as outlined in Tables 2 and 4. Mean concentrations of the data obtained in each of these legs are used in this analysis. The CCN measurements were made continuously at a rate of 1–3 s⁻¹ with less than a tenth of a second of dead time between each measurement. In POST there was one below-cloud CCN measurement for each of the original 28 cloud passes, thus the same CCN measurement was used for both sections of the 6 divided passes. The POST CCN measurements were made well below cloud base at either 30- or 100-m altitude before or after each of the cloud passes (Tables 2 and 4). Because of the lower cloud bases and greater speed of the MASE airplane, CCN measurement legs were usually very close to cloud base at ~100-m altitude. Since cloud-free air at these altitudes was limited in MASE, there were only 26 separate CCN measurements that had to be used for the 38 original cloud passes, and as in POST, there was only one CCN measurement for both sides of the 12 divided cloud passes.

FIG. 3. (a) Revision of Fig. 2 of H10, and (b) revision of Fig. 4 of H10. These show $S_{\text{eff}}$ against $N_{1\%}$ for 69 vertical penetrations in (a) and 34 horizontal penetrations of POST clouds. The $S_{\text{eff}}$ is the $S$ for which nearby below-cloud $N_{\text{CCN}}(S)$ equals mean $N_c$. Major corrected data for 18 Jul are denoted in green. Linear regression lines and correlation coefficients $R$ are shown.

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passes. Therefore, many more of the MASE cloud passes used the same CCN measurements, especially within the flights with the largest numbers of cloud passes.

Table 4 outlines the lengths of the cloud passes and CCN measurement paths used here along with characterizations of the separations between each of the clouds from their corresponding CCN measurements. The separations between cloud and corresponding CCN measurements usually consisted of slant path ascents or descents, data from which are not considered here. These separations shown in Table 4 are maximum possible distances because, for simplicity, they assume that the airplane continued to fly in straight lines for each cloud and corresponding CCN measurement and separation between them. Since this was not always the case, especially for MASE where the airplane usually flew back through the same clouds at different altitudes in opposite directions, the distance separations are often overestimated. However, this does not reduce the corresponding time differences between the CCN and cloud measurements, which can be computed from the airspeed. During those separation periods the air in the regions of the measurements could have changed anyway. On the other hand, Table 5 indicates that there were relatively small differences in \( N_c \) and \( N_{CCN} \) within the flights. Thus, Table 6 shows that the correlation coefficients (\( R \); Pearson product moment) based on flight averages were similar to corresponding \( R \) based on all of the individual clouds in each project. Furthermore, H10 showed the same \( N_{1\%} - N_c \) \( R \) values for vertical cloud penetrations that had much smaller distance and time separations than the separations between horizontal cloud penetrations and their corresponding below-cloud CCN measurements.

Cloud passes during POST were made at only one altitude for each cloud. Multiple altitude cloud passes were done in MASE during six of the nine flights. The \( N_c \) was roughly constant with altitude for three of these flights and increased by \( \sim 25\% \) with altitude for two flights and increased by \( \sim 50\% \) with altitude in the highest-altitude MASE flight. Cloud pass altitudes were confined to 150–440 m for all but one MASE flight where they ranged from 560 to 700 m. In MASE divisions of data according to altitude showed little difference from correlations that considered all MASE cloud altitudes. Nevertheless, the altitude differences of the MASE clouds are a source of uncertainty.

Since \( W \) measurements are less reliable during altitude changes, data during slant soundings are not considered in this analysis. The \( W \) was recorded at 10 Hz in both projects. The \( W \) considered here are means of all of these measurements where LWC of the CAS exceeded 0.1 g m\(^{-3}\) within each of the 34 and 50 cloud passes. There is also consideration of the standard deviations of \( W \) (\( \sigma_w \)), which was computed from the same 10-Hz \( W \) measurements.

### 3. Corrections of H10

Estimates of stratus cloud supersaturations \( S \) during POST (H10) demonstrated the reduction of cloud \( S \) [effective supersaturation; \( S_{eff} \); \( S \) for which \( N_{CCN}(S) = N_c \)] by the competition among cloud droplets brought about by high \( N_{CCN} \) as had been predicted by Twomey (1959, hereafter T59). However, it has since been discovered that an incorrect calibration was applied to the CCN spectra for the POST flight with the highest \( N_{CCN} \) and \( N_c \). This produced erroneously low \( S_{eff} \) estimates for 18 July, which had provided 8 of the 69 vertical cloud penetrations shown in Fig. 2 of H10 and 3 of the 28 horizontal penetrations shown in Fig. 4 of H10. Figure 3 here shows corrected versions of those two H10 figures. There was also a minor correction for the 4 August flight that slightly adjusted 7 vertical (Fig. 2 of H10, Fig. 3a here) and 3 horizontal (Fig. 4 of H10, Fig. 3b here) data points and there were a few other tiny revisions. Also the \( S_{eff} \) here are more precise because all CCN channels

### Table 5. Variations in terms of the standard deviations/means of \( N_c \) for the 11 POST flights and 8 MASE flights with multiple cloud passes (columns 2–4) and of the CCN concentrations at 1% \( S \) for the 10 POST flights and 8 MASE flights with multiple CCN measurements.

<table>
<thead>
<tr>
<th>Proj</th>
<th>Mean, std dev of ( N_c ) std dev/mean</th>
<th>Min ( N_c ) std dev/mean</th>
<th>Max ( N_c ) std dev/mean</th>
<th>Mean, std dev of ( N_{1%} ) std dev/mean</th>
<th>Min ( N_{1%} ) std dev/mean</th>
<th>Max ( N_{1%} ) std dev/mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>POST</td>
<td>0.15 ±0.09 0.09 0.48 0.16 ±0.12 0.04 0.38</td>
<td>0.02 0.34 0.04 0.16 0.04 0.38</td>
<td>0.01 0.48 0.04 0.15 0.04 0.36</td>
<td>0.17 ±0.15 0.09 0.48 0.16 ±0.12 0.04 0.38</td>
<td>0.02 0.34 0.04 0.16 0.04 0.38</td>
<td>0.01 0.48 0.04 0.15 0.04 0.36</td>
</tr>
</tbody>
</table>
were used to determine $S_{\text{eff}}$ rather than interpolations between $10^{\text{NCCN}}$ channels in H10.

The horizontal data (Fig. 3b) also add 6 data points because 6 of the original horizontal cloud penetrations have been divided because of abrupt differences in $N_c$ and $W$ during these penetrations (Fig. 4a); thus 34 instead of 28 data points. Nonetheless, these revised figures still exhibit the decrease of $S_{\text{eff}}$ with $N_{\text{CCN}}$, although $S_{\text{eff}}$ remained above 0.1% even for the most polluted POST flight of 18 July. Figures 1 and 3 of H10 [$N_c$ versus $N_{\text{CCN}}$ at 1% $S(N_{1\%})$] are imperceptibly changed because the calibration corrections affected only lower $S_{\text{CCN}}$ and not $N_{1\%}$. Revisions of those two figures still show the expected high positive correlation between $N_{1\%}$ and $N_c$—for example, Fig. 5a, which is an update of Fig. 1 of H10.

4. Influences on cloud droplet concentrations $N_c$

Figure 6a shows the $R$ patterns between $N_{1\%}$ and cumulative droplet concentrations larger than various threshold sizes $N_r$—that is, the $R$ of $N_c$ versus $N_{\text{CCN}}$ at 1% $S(N_{1\%})$ are imperceptibly changed because the correction affected only lower $S_{\text{CCN}}$ and not $N_{1\%}$. Revisions of those two figures still show the expected high positive correlation between $N_{1\%}$ and $N_r$—for example, Fig. 5a, which is an update of Fig. 1 of H10.

In complete contrast with POST and probably every other comparison between $N_{\text{CCN}}$ and $N_c$ (e.g., Hudson...
and Yum 2001, 2002; Conant et al. 2004; Yum et al. 1998; Yum and Hudson 2002, 2004; Hudson and Noble 2009; Hegg et al. 2012; Antilla et al. 2012) or any aerosol measurement with \( N_c \) (Leaitch et al. 1992, 1996; Twohy et al. 2005; Peng et al. 2005; Lu et al. 2007) Figs. 5b and 6a (red squares) and Fig. 7 (red squares) show inverse \( N_{CCN} - N_c \) relationships for 50 horizontal cloud penetrations during MASE. Figure 5c puts data from the two projects together (Figs. 5a,b) to show that they overlap within the middle \( N_{1\%} \) range of 350–800 cm\(^{-3}\). Figure 5c then displays the decrease in the slope of \( N_c - N_{1\%} \), which is referred to as roll off, which occurs because competition among droplets reduces cloud \( S \) as shown in Fig. 3. Furthermore, Fig. 5c shows more than a reduction of the slope, but here there is even a reversal of the \( N_c - N_{1\%} \) slope to negative values for the high \( N_{1\%} \) of MASE.

On the other hand, \( N_{CCN} \) is not the only factor that determines \( N_c \); the vertical velocity (\( W \)) is the second major influence on initial \( N_c \). Consistent with this H10 showed positive relationships between \( W \) and \( N_c \) in POST though with lower \( R \) than \( N_{CCN} - N_c \)—that is, Figs. 8a and 6b (black). Such expected positive relationships between \( W \) and \( N_c \) have been previously reported (Leaitch et al. 1996; Snider and Brenguier 2000; Conant et al. 2004; Peng et al. 2005; Hudson et al. 2010b). Since both \( N_{CCN} \) and \( W \) should and indeed do display positive influences on \( N_c \), in POST a multiple regression analysis ought to show a higher \( R \) than \( R \) of either \( N_{CCN} - N_c \) or \( W - N_c \). However, such a multiple regression instead shows an \( R \) that only equals the \( R \) of \( W - N_c \). The reason for this curious result is the unexpected positive \( R \) between \( N_{1\%} \) and \( W \) (H10) that is of similar magnitude (0.54, Fig. 9a) to \( R \) of \( W - N_c \) (0.60, Fig. 8a). Gray diamonds in Fig. 7 show multiple significantly positive \( R \) of \( N_{CCN} \) and \( W \) measured where CCN were measured with \( N_t \), and \( R \) of \( W \) and \( S_w \) measured over more extensive low altitudes with \( N_t \).

It is also somewhat unexpected that there are finite and somewhat large values of \( W \) within each POST cloud pass (e.g., Fig. 4a, blue line; maximum mean \( W \) range \(-40 \) to \(+40 \) cm s\(^{-1}\) in Figs. 8a and 9a) because...
stratus cloud $W$ is usually thought to average zero over sufficient distances (e.g., Leaitch et al. 1996; Peng et al. 2005). Possibly the POST cloud passes were not long enough to produce near-zero mean $W$ (Table 4). However, this did not seem to be the case for the MASE cloud penetrations, which consistently showed mean $W$ so close to zero (maximum range $-4$ to $+2$ cm s$^{-1}$; Fig. 8b) during all MASE horizontal cloud passes that the tiny mean $W$ of the MASE clouds was not correlated with cloud microphysical variables, especially mean $N_c$ ($R = 0.04$ in Fig. 8b and Table 6, 0.07 for flight averages—or with any $N_t$, Fig. 6c, black line). Although the MASE cloud passes were on average a factor of 3 longer than those of POST (Table 4, column 2) there was considerable overlap of the durations of the cloud passes between the two projects (Table 4, column 2, std dev). Although, absolute values of mean $W$ are larger for the shorter MASE durations, $R$ of $N_c$–$W$ for the 10 MASE passes with durations less than the median duration of the POST passes (17 of 34) is 0.15. Furthermore, $R$ for the 21 MASE passes with durations less than the mean of the POST passes (21 of 34) is 0.06. Thus, the durations of the cloud passes do not seem to be the reasons for the differences in cloud dynamics between these two projects in the same area, season, and cloud type. More to the point, Twin Otter measurements obtained on the three MASE days when both airplanes flew (15–17 July) also showed the same magnitude differences in mean $W$ during scores of horizontal cloud penetrations. Lu et al. (2009) also found similar large mean $W$ in MASE-II. It is thus much more likely that the different methods of measuring and interpreting $W$ between the two different aircraft were probably the reasons for the differences in apparent $W$ behavior between the two projects. The slower speed and smaller size of the Twin Otter probably made it more difficult to discount the airplane motions in response to air motions. It may also be possible that the smaller, slower airplane has greater sensitivity to $W$ or that its $W$ measurement system is more sensitive.

It is often thought that in stratus clouds the variability of $W$, that is, the standard deviation of $W$ ($\sigma_w$), can be a surrogate for $W$ (Leaitch et al. 1996; Peng et al. 2005). Indeed Figs. 10b and 6c (red line) show that mean $N_c$ and $N_t$ seemed to respond to $\sigma_w$ during MASE ($\sigma_w$–$N_c$, $R = 0.51$) and not to mean $W$ (Fig. 8b; $R = 0.04$; Fig. 6c black line). An even higher $R$ of 0.58 is found in MASE for $\sigma_w$ with 90th percentiles of $N_c$ (top decile, $N_{10}$), which will be shown later to approximate adiabatic $N_c$ ($N_a$). In POST, $\sigma_w$–$N_c$ was only 0.28 (Fig. 10a and green line in

![Fig. 8. (a) Mean $N_c$ vs $W$ for 34 POST horizontal cloud passes and (b) 50 MASE horizontal cloud passes. Linear regressions are shown. Note the different units on the abscissas.](image-url)
POST suggests that the $R$ of $N_{CCN} - N_c$ and $W - N_c$ are both enhanced by the influence of the other factor. To illustrate the effect of the interactions of the two major influences on $N_c$ we chose a subset of the POST data with $R$ of $W - N_{1\%}$ that is neutral (uncorrelated). This is demonstrated by the green triangles in Fig. 11. The 23 green points in Fig. 11a have a neutral $R$ of 0.01, which is quite different from the positive $R$ of 0.54 for all 34 POST data points in Fig. 9a. Figure 11b then shows the lower 0.74 $R$ for $N_c - N_{1\%}$ for this data subset than the 0.86 $R$ for the entire POST dataset (Fig. 5a). Then Fig. 11c shows that this same data subset has a neutral ($R = -0.08$) $W - N_c$ relationship that thus does not enhance the $N_c - N_{1\%}$ relationship as is the case for the entire POST data set where $N_c - W$ is positively related ($R = 0.60$, Fig. 8a).

So far $W$ and $\sigma_w$ within the clouds have been considered. For the purposes of determining the dynamic influences on initial cloud microphysics (i.e., $N_c$) $W$ or $\sigma_w$ measurements should have been made just below or just above cloud base. But these are stratus clouds, which have longer lifetimes that do not fit the cloud base formation processes of cumulus clouds. At any rate, Fig. 6b (POST) shows that $W$ and $\sigma_w$ measured below cloud also showed positive $R$ with small size threshold $N_i$ ($<\sim 10\mu m$), albeit with lower $R$ than within-cloud $W$ and $\sigma_w$, except that the more extensive below-cloud $\sigma_w$ (low) has a higher $R$ than the within-cloud $\sigma_w$ with $N_i$. Furthermore, Fig. 6c (MASE) shows that both below-cloud $\sigma_w$ measurements have nearly as high $R$ with small size threshold $N_i$ as the within-cloud $\sigma_w$ measurements have with small threshold $N_c$.

5. Effects on cloud supersaturation $S_{\text{eff}}$

H10 noted that estimates of $S_{\text{eff}}$ by comparing CCN spectra with mean $N_c$ are underestimates of the $S$ at cloud base that determines initial $N_c$, which is the most closely related to $N_{CCN}$ (e.g., Hegg et al. 2012). This is because mean $N_c$ has often been reduced by entrainment, which is not expected to depend on aerosol characteristics. Entrainment also inherently reduces LWC below adiabatic values. Figure 12 demonstrates estimates of adiabatic $N_c$ in POST by using the ratio of measured LWC to adiabatic LWC ($\text{LWC}_{\text{adia}}$) (Hudson and Yum 2001, 2002). $\text{LWC}_{\text{adia}}$ is calculated from cloud-base temperature, pressure, and altitude for the altitude of each $N_c$ measurement. The assumption of identical cloud-base altitude, pressure, and temperature throughout each horizontal cloud penetration is an uncertainty of this technique and so is the difficulty of ascertaining cloud base, which was done during vertical slant ascents or descents prior or after each horizontal cloud pass. During POST 31 of the 34 horizontal cloud passes displayed...
patterns similar to the examples in Fig. 12 where there are linear relationships between measured $N_c$ and measured LWC/LWC$_{adia}$ for which extrapolations of the regressions provide $N_c$ at LWC/LWC$_{adia} = 1.0$. These adiabatic $N_c$ are $N_a$, which should be the $N_c$ most closely related to the input CCN. The $N_a$ are then compared with below-cloud $N_{CCN}(S)$ to produce alternate $S_{eff}$ estimates that are displayed in Fig. 13a, which also shows $S_{eff}$ based on mean $N_t$ that were displayed in Fig. 3b. Figure 13a also uses another estimate of $N_a$, the 90th percentile of $N_c$ measurements $N_{td}$ within each cloud pass. The $N_{td}$ was also employed by H10. Figure 13b shows similar $S_{eff}$ estimates for MASE, absent $N_a$ because $N_a$ could not always be estimated because of the difficulty of determining cloud base in MASE. The agreement between the $N_a$ and $N_{td}$ estimates of $S_{eff}$ in Fig. 13a (POST) gives credence to the utility of the $N_{td}$ estimates of $S_{eff}$ in MASE (Fig. 13b). Figure 13c shows $S_{eff}$ consistency between POST and MASE within the overlapping $N_{1\%}$ range (380–800 cm$^{-3}$) and the overall decrease of $S_{eff}$ with $N_{1\%}$ that was shown in Fig. 3. Table 7 shows the average $S_{eff}$ within three $N_{1\%}$ bins for each project. Because of the vast difference in $N_{1\%}$ between the two projects it is not practical to use the same bins in each project because they would not have a sufficient number of cases. Nevertheless, Table 7 does show rather good agreement between the two projects, both of which show the decrease of $S_{eff}$ with $N_{1\%}$, and the higher $S_{eff}$ by using mean $N_{td}$ rather than mean $N_c$ as well as the slightly higher but agreeable $S_{eff}$ by using mean $N_a$ for POST that is also displayed in Fig. 13a.

Low $S_{eff}$ so frequently displayed in Figs. 3 and 13, especially for MASE, indicate that $N_{1\%}$ might not be the most appropriate $N_{CCN}$. Figure 14, however, shows that $R$ for $S_{eff}$ with $N_{CCN}$ at various $S$ is consistent over wide ranges of $S$ in both projects. Although the slopes and $R$ of the regressions are smaller for $S_{eff}$–$N_{CCN}$ at lower $S$ they are not positive for any $S_{eff}$–$N_{CCN}$ in either project. In POST, $N_{CCN}$–$N_c$ relationships are positive at all $S$, albeit the slopes are higher and the $R$ values are progressively smaller for lower $S$ (Fig. 7; black, blue and green data points).

Though higher $W$ should produce higher $S_{eff}$, Fig. 15a shows negative $R$ for $S_{eff}$–$W$. This occurs because of the coupling of $W$ with $N_{1\%}$ in POST (Fig. 9a). The gray diamonds in Fig. 7 show that in POST this $W$–$N_{CCN}$ coupling exists for $N_{CCN}$ at all measured $S$. Therefore, higher $N_{CCN}$ comes along with the higher $W$ and this makes even higher $N_c$ than that due to just the higher $W$. The greater droplet surface area of the higher $N_c$ reduces $S_{eff}$ because of the competition among the droplets for condensate as demonstrated in Figs. 3 and 13. Thus, in POST the negative $N_{CCN}$ effect on $S_{eff}$ prevails over the positive $W$ influence on $S_{eff}$. This is demonstrated by the black, blue, and green data points in Fig. 7 where $R$ for $N_{CCN}$–$N_c$ for $S > 0.08\%$ is greater than the $0.60 R$ for $W$–$N_c$ shown in Fig. 8a. Figure 15b, on
other hand, does show positive $R$ for $S_{\text{eff}}$-$\sigma_w$ because the lack of coupling between $\sigma_w$ and $N_{\text{CCN}}$ in MASE (Fig. 9b and dark pink in Fig. 7) does not bring higher $N_{\text{CCN}}$ along with higher $W$. This allows the positive influence of $\sigma_w$ on $N_c$ (Fig. 10b) to go unhindered in MASE and thus produce the positive $R$ of $S_{\text{eff}}$-$\sigma_w$, shown in Fig. 15b. Moreover, the strong positive influence of $N_{\text{CCN}}$ on $N_c$ in POST shown in Fig. 5a and further in Fig. 7 (black, blue, and green data points for nearly all $S$) does not exist in MASE (Figs. 5b) where this $R$ is even negative for $N_{\text{CCN}}$ at all $S$ as shown by the red and pink data points in Fig. 7. The $S_{\text{eff}}$ calculated from mean $N_c$, $N_w$, or $N_{\text{id}}$ show the same trends with $W$ in POST and with $\sigma_w$ in MASE.

Although it might seem that $N_c$ should be positively related to cloud $S$, Fig. 16 displays a negative $S_{\text{eff}}$-$N_c$ relationship for POST. This is because the lower $S_{\text{eff}}$ estimates occur when $N_{\text{CCN}}$ is higher, which then produce higher $N_c$—that is, even though a smaller proportion of CCN activate to droplets when $S_{\text{eff}}$ is lower the number of activated droplets is still larger than is the case for cleaner conditions when greater percentages of CCN activate out of the lower $N_{\text{CCN}}$. This is elucidated in Table 3, column 13, by the higher mean activation ratio ($N_c/N_{1\%}$) of POST. Thus, in POST $N_c$ is still higher when $N_{\text{CCN}}$ is higher because of the greater influence of $N_{\text{CCN}}$ than $W$ on $N_c$ and the positive coupling of $N_{\text{CCN}}$ with $W$. In MASE the lack of apparent influence of $N_{\text{CCN}}$ on $N_c$ allows the $\sigma_w$ influence on $N_c$ to prevail. Thus, higher $\sigma_w$ force a higher percentage of CCN to activate to droplets, which generally produces higher $N_c$ and $S_{\text{eff}}$. The lower $S_{\text{eff}}$ for higher $N_{\text{CCN}}$ in MASE ($N_{1\%}$ in Figs. 13b,c) results from the lack of coupling between $\sigma_w$ and $N_{\text{CCN}}$, that is, within each $N_{\text{CCN}}$ ($N_{1\%}$) band a similar mix of $\sigma_w$ will activate a smaller percentage of CCN to droplets when $N_{\text{CCN}}$ is higher and a larger percentage of $N_{\text{CCN}}$ to droplets when $N_{\text{CCN}}$ is lower thus making the descending $S_{\text{eff}}$-$N_{1\%}$ relationships shown in Figs. 13b and 13c. The fact that there are different reasons for the similar relationships of the two projects in Fig. 13 is reflected in the very different relationships shown in Fig. 16—that is, the predominant $N_{\text{CCN}}$ influence in POST and the predominant $\sigma_w$ influence in MASE.

The difference between the two major influences on $N_c$ exhibited by POST and MASE was predicted by T59. That explanation lies in the differences of the slopes ($k$) of the cumulative CCN spectra at and below $S_{\text{eff}}$ shown.
in Fig. 1b and Table 3, last column. At the lower values of \( S_{\text{eff}} \) of MASE \( k \) is higher than the lower \( k \) at the higher \( S_{\text{eff}} \) of most of POST. Table 8 displays the exponents of \( N_{1\%} \) and \( W \) of the T59 equation

\[
N_c \propto N_{1\%}^{[1-\frac{k}{k(2+k)}]} W^{3k/[2(2+k)]]}
\]  

for various \( k \). Equation (1) and Table 8 demonstrate the increasing influence of \( W \) and decreasing influence of \( N_{\text{CCN}} \) as \( k \) increases. Twomey (1977b, p. 104) presented the same equation and pointed out that for \( k \ll 1.0, N_c \) is approximately proportional to \( N_{1\%} \) but for \( k \gg 1.0, N_c \) is approximately proportional to \( W \). "Had the slope of natural supersaturation spectra proved to be large the drop concentration in cloud would have been determined almost exclusively by the dynamics of the environment in which the cloud formed rather than the aerosol content."

The same differences of \( W \) or \( \sigma_w \) produce greater differences in \( N_c \) at higher \( k \) than at lower \( k \). For MASE the transition from predominant \( N_{\text{CCN}} \) influence to predominant \( \sigma_w \) influence on \( N_c \) occurred at a lower \( k \) (<0.8) than predicted by T59 (\( k = 1.33 \)).

6. Divided cloud passes

Table 9 details the six divided POST horizontal cloud passes, an example of which is displayed in Fig. 4a. The second and third columns show the mean \( W \) of the higher and lower \( W \) portions of each divided cloud leg. The fourth, fifth, and sixth columns show the mean \( N_c \), \( N_a \), and \( N_{td} \) of each of the respective portions of each flight leg. Mean \( N_c \) is higher for the leg portions with higher mean \( W \) in four of the six cases while mean \( N_a \) and \( N_{td} \) are higher for five of the six leg portions with higher mean \( W \). Mean \( N_a \) and \( N_{td} \) are more pertinent to initial \( N_{\text{CCN}} \) and \( W \) because mean \( N_c \) are more likely to be reduced by entrainment. The two \( N_c \) exceptions, 28 July and 1 August, have the smallest and third smallest mean \( W \) differences and the smallest mean \( N_c \) differences between the two divisions of their cloud passes out of the six complete cloud passes considered in Table 9. The 1 August exception for all three droplet concentrations (lower for the higher \( W \) portion) has nearly the lowest \( N_{td} \) difference; 28 July has only 1 cm\(^2\) smaller \( N_{td} \) difference in the opposite direction, higher for higher \( W \). The 1 August exception has by far the lowest \( LWC \) and average ratio of measured to adiabatic \( LWC \) of any of the passes (column 7), which makes a much greater and more uncertain extrapolation of the linear regression of the data points to \( LWC/LWC_{\text{adia}} = 1 \) that is needed to estimate \( N_a \) (see Fig. 12). Furthermore, the distribution of data points (e.g., Fig. 12) for the high mean \( W \) portion of the 1 August distribution is flat whereas this distribution for the lower \( W \) portion is very steep. These are the reasons for the lower \( N_a \) estimate for the high mean \( W \) portion of this leg and the higher \( N_a \) estimate for the lower mean \( W \) portion of the 1 August divided cloud.

| POST | \( N_{1\%} \) (cm\(^{-3}\)) | \( S_{\text{eff}} \) (%) \( (N_c) \) | \( S_{\text{eff}} \) (%) \( (N_{td}) \) | \( S_{\text{eff}} \) (%) \( (N_a) \) |
|---|---|---|---|
| <200 | 0.967 | 1.286 | 1.340 |
| 200–400 | 0.475 | 0.641 | 0.683 |
| >400 | 0.175 | 0.200 | 0.202 |

| MASE | \( N_{1\%} \) (cm\(^{-3}\)) | \( S_{\text{eff}} \) (%) \( (N_c) \) | \( S_{\text{eff}} \) (%) \( (N_{td}) \) | \( S_{\text{eff}} \) (%) \( (N_a) \) |
|---|---|---|---|
| <500 | 0.421 | 0.429 | 0.571 |
| 500–700 | 0.128 | 0.178 | 0.281 |
| >700 | 0.123 | 0.160 | 0.180 |

FIG. 13. (a) As in Fig. 3b, but with the addition of estimates based on \( N_a \) and \( N_{td} \). (b) As in (a), but for MASE. (c) Combination of (a),(b) for \( N_{td} \).
It must be assumed that $N_{CCN}$ is the same for both sections of each of the divided cloud passes. The $N_{CCN}$ differences on scales as small as the two divisions of each of the cloud passes are unlikely (Table 5, columns 5–7) and thus unlikely to be the cause of the $N_c$ differences (Table 5, columns 2–4) between the divisions of the cloud passes (Table 6), especially since the $W$ differences are generally commensurate with the $N_c$, $N_a$, and $N_{td}$ differences that are shown in Table 9. The $R$ of the linear regressions $N_{1\%–N_c}$, $N_{1\%–N_{td}}$, $W–N_c$, and $W–N_{td}$ are all higher for the 12 data points in Table 9 than the corresponding $R$ values for the entire 34 case dataset.

Table 10 shows the analogous set of divided cloud passes from MASE; Fig. 4b is an example. The running $\sigma_w$ in Fig. 4b do not correspond with the overall $\sigma_w$ because they are with respect to the 50 record (5 s) running-mean $W$ whereas the overall $\sigma_w$ is with respect to the mean $W$ over the entirety of each cloud section. In all 12 cases there were substantially higher $N_c$ (column 4) and $N_{td}$ (column 5) for the legs with higher $\sigma_w$. Moreover, the $\sigma_w$ differences between each of the adjacent legs were usually substantial. Column 8 shows that mean $W$ was lower for 5 of the 12 legs with higher $\sigma_w$, $N_c$, and $N_{td}$, thus again mean $W$ does not correlate in MASE. As in POST the same $N_{CCN}$ is assumed for both divisions of each of the 12 cloud legs and it seems unlikely that $N_{CCN}$ would display differences on such a small scale (i.e., Table 5, columns 5–7) that are as drastic as the $N_c$ differences (Table 5, columns 2–4). Since the $N_c$ and $N_{td}$ differences between each of the adjacent cloud legs correspond to the $\sigma_w$ differences, it is likely that $\sigma_w$ is the cause of the $N_c$ and $N_{td}$ differences in each of the 12 adjacent cloud legs. This is especially so since 10 of the 12 $N_c$ and $N_{td}$ values are more than 39% higher for the legs with higher $\sigma_w$.
and 21% higher in the higher $\sigma_w$ than the lower $\sigma_w$ sections of each leg. Furthermore, 4 of 12 cases have more than a factor of 2 higher $N_c$ and more than 61% higher $N_{td}$ in the higher $\sigma_w$ sections of each leg. The $R$ values of $N_{1\%} - N_c$, $N_{1\%} - N_{td}$, $\sigma_w - N_c$, and $\sigma_w - N_{td}$ for these 24 cases are all similar to the corresponding $R$ values of the entire 50-case MASE dataset. The huge $N_c$ and $N_{td}$ differences for the same aerosol inputs and the negative $R$ for $N_{CCN} - N_c$ and $N_{CCN} - N_{td}$ and the consistently higher $N_c$ and $N_{td}$ for the higher $\sigma_w$ divisions of each of the 12 divided cloud legs indicate the impossibility that any aerosol parameter can positively correlate with $N_c$ or $N_{td}$ in MASE.

Questions about the viability of the $W$ and $\sigma_w$ measurements are answered in Tables 9 and 10 where adjacent pairs of cloud passes display distinct contrasts in $N_c$ and $W$ (POST) or $\sigma_w$ (MASE) (Fig. 4). Another possibility for the cause of the droplet concentration differences would be the injection of higher $N_{CCN}$ from above the clouds, which might be more likely with higher $W$ or $\sigma_w$. However, H10 showed that in POST there was no difference in the $N_{1\%} - N_c$ $R$ for situations with higher total particle (condensation nuclei; $N_{CCN}$) concentrations above the clouds than below the clouds than for situations with the same or lower $N_{CCN}$ above the clouds compared to below the clouds. The $N_{CCN}$ was used for this purpose because the faster response of the CN counter provided better separation from the undesired splashing artifacts of in-cloud measurements and since $N_{CCN}$ are generally proportional to $N_{CCN}$. Above-cloud $N_{CCN}$ did not seem to be the cause of the differences in three of the six POST cases because there were lower or the same $N_{CCN}$ above the clouds for these cases. The large differences of mean $W$ (POST) and $\sigma_w$ (MASE) between the divisions of each of the divided cloud passes are more than adequate to produce the observed mean $N_c$ differences between the divisions of each pass without any help of injections of above-cloud aerosol.

7. CCN–vertical velocity relationships

The correlation between $N_{CCN}$ and mean $W$ in POST may just be coincidental—that is, the airplane happened to go through high $W$ cloud regions when $N_{CCN}$ was higher. Nonetheless, the enhancement of $N_c$ by higher $W$ was a fact to deal with regardless of the cause. Moreover, if stratus clouds have near-zero mean $W$ over sufficient distances (Leaitch et al. 1996; Peng et al. 2005) then $W - N_{CCN}$ coupling does seem merely coincidental. However, this does not preclude $\sigma_w - N_{CCN}$ coupling in stratus. Although $\sigma_w$ in POST does not display as high $R$ as $W$ (Fig. 8a) with either $N_c$ (Fig. 10a) or $N_c$ (Fig. 6b) or $N_{CCN}$ (Fig. 17) all $Rs$ for $\sigma_w$ in POST are consistently positive, except those with $N_c$ for thresholds $>10\mu m$; this is similar to other $R$ values for these large sizes in Fig. 6b.

---

Table 8. Exponents of the two main factors that determine $N_c$ by the equation of Twomey (1959).

<table>
<thead>
<tr>
<th>$k$</th>
<th>$N_{1%}$</th>
<th>$W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.91</td>
<td>0.14</td>
</tr>
<tr>
<td>0.42</td>
<td>0.83</td>
<td>0.26</td>
</tr>
<tr>
<td>0.50</td>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>0.52</td>
<td>0.79</td>
<td>0.31</td>
</tr>
<tr>
<td>0.75</td>
<td>0.73</td>
<td>0.41</td>
</tr>
<tr>
<td>0.82</td>
<td>0.71</td>
<td>0.44</td>
</tr>
<tr>
<td>1.00</td>
<td>0.67</td>
<td>0.50</td>
</tr>
<tr>
<td>1.33</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>2.00</td>
<td>0.50</td>
<td>0.75</td>
</tr>
<tr>
<td>3.00</td>
<td>0.40</td>
<td>0.90</td>
</tr>
<tr>
<td>4.00</td>
<td>0.33</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 9. Six pairs of POST adjacent cloud segments divided according to abrupt major differences in mean $W$ and $N_c$; example in Fig. 4a. Column 2 is the mean $W$ of the cloud portion with the higher mean $W$, column 3 is the mean $W$ of the lower mean $W$ portion, column 4 shows the mean $N_c$ of the higher and lower $W$ portions of each cloud leg, column 5 shows the $N_c$ of each cloud portion, column 6 is the $N_{td}$ of each cloud division, column 7 is the mean cloud (CAS) LWC of each cloud section, column 8 is mean drizzle (CIP) LWC of each section, column 9 is $\sigma_w$ of each section, and column 10 shows the durations of each cloud leg. The bottom rows labeled x1A are the mean and std dev of the five rows exclusive of 1 Aug.

<table>
<thead>
<tr>
<th>Date</th>
<th>$H\ W$ (cm s$^{-1}$)</th>
<th>$L\ W$ (cm s$^{-1}$)</th>
<th>$N_c$ (H–L) (cm s$^{-3}$)</th>
<th>$N_c$ (L–H) (cm s$^{-3}$)</th>
<th>$N_{td}$ (H–L) (cm s$^{-3}$)</th>
<th>$L_c$ (H–L) (g m$^{-3}$)</th>
<th>$L_c$ (L–H) (g m$^{-3}$)</th>
<th>$\sigma_w$ (H–L) (mg m$^{-3}$)</th>
<th>$\sigma_w$ (L–H) (mg m$^{-3}$)</th>
<th>Dur (H–L) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 Jul</td>
<td>34.5</td>
<td>0.7</td>
<td>377–298</td>
<td>403–377</td>
<td>420–343</td>
<td>0.36–0.31</td>
<td>0.90–21.3</td>
<td>80.2–59.1</td>
<td>44–94</td>
<td></td>
</tr>
<tr>
<td>18 Jul</td>
<td>36.5</td>
<td>6.4</td>
<td>367–322</td>
<td>390–336</td>
<td>407–352</td>
<td>0.35–0.36</td>
<td>0.58–3.40</td>
<td>55.5–63.0</td>
<td>72–65</td>
<td></td>
</tr>
<tr>
<td>28 Jul</td>
<td>26.3</td>
<td>23.9</td>
<td>192–223</td>
<td>264–258</td>
<td>240–223</td>
<td>0.33–0.36</td>
<td>0.13–1.00</td>
<td>71.6–95.9</td>
<td>43–42</td>
<td></td>
</tr>
<tr>
<td>1 Aug</td>
<td>0.8</td>
<td>−9.3</td>
<td>75–92</td>
<td>77–313</td>
<td>85–103</td>
<td>0.16–0.12</td>
<td>5.50–8.72</td>
<td>30.7–22.1</td>
<td>191–295</td>
<td></td>
</tr>
<tr>
<td>8 Aug</td>
<td>−21.1</td>
<td>−27.2</td>
<td>127–84</td>
<td>213–115</td>
<td>192–109</td>
<td>0.31–0.35</td>
<td>8.77–6.69</td>
<td>43.9–42.7</td>
<td>217–222</td>
<td></td>
</tr>
<tr>
<td>12 Aug</td>
<td>14.54</td>
<td>2.2</td>
<td>183–127</td>
<td>205–155</td>
<td>217–147</td>
<td>0.28–0.26</td>
<td>2.43–1.45</td>
<td>44.4–40.0</td>
<td>202–258</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>15.26</td>
<td>−0.78</td>
<td>220–191</td>
<td>259–259</td>
<td>260–213</td>
<td>0.30–0.29</td>
<td>3.84–7.09</td>
<td>54.4–53.8</td>
<td>128–163</td>
<td></td>
</tr>
<tr>
<td>Std dev</td>
<td>22.25</td>
<td>16.97</td>
<td>125–105</td>
<td>123–104</td>
<td>130–113</td>
<td>0.07–0.09</td>
<td>3.27–7.58</td>
<td>18.6–25.3</td>
<td>83–109</td>
<td></td>
</tr>
<tr>
<td>Mean-x1A</td>
<td>18.15</td>
<td>0.92</td>
<td>249–211</td>
<td>295–248</td>
<td>295–235</td>
<td>0.33–0.33</td>
<td>3.50–6.77</td>
<td>59.1–60.1</td>
<td>116–136</td>
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<tr>
<td>Std dev-x1A</td>
<td>23.58</td>
<td>18.39</td>
<td>115–104</td>
<td>95–113</td>
<td>109–111</td>
<td>0.03–0.04</td>
<td>3.54–8.43</td>
<td>16.3–22.3</td>
<td>87–97</td>
<td></td>
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</tbody>
</table>
There are two theories that suggest $\sigma_w$–$N_{\text{CCN}}$ coupling, both of which involve differential latent heat exchange. Jiang et al. (2002, 2010) and Ackerman et al. (2004) suggested that since evaporation of drizzle below cloud tends to stabilize the boundary layer, precipitation suppression by higher $N_{\text{CCN}}$ should result in reduced stabilization of the boundary layer. Such a reduction of evaporative cooling below cloud would then increase TKE and buoyancy, which would result in an increase of $\sigma_w$. This should then result in a negative $R$ between drizzle (LWC of the CIP, $L_d$) and $\sigma_w$ below cloud base where evaporation of drizzle occurs. Table 11, rows 1–3, shows that in both projects there is less precipitation when $N_c$ is higher, which tends to be associated with smaller mean diameter (MD; row 2) and narrower droplet spectra ($\sigma_c$; row 3), which inhibit $L_d$. Row 4

![Figure 17](image-url)

**Table 10.** As in Table 9, but for MASE. The 12 pairs of adjacent divided cloud passes based on abrupt differences in $\sigma_w$ and $N_c$ (Fig. 4b is an example). Column 2 is $\sigma_w$ of the higher $\sigma_w$ portion, column 3 is $\sigma_w$ of the lower $\sigma_w$ portion, column 4 is the mean $N_c$ of the higher and lower $\sigma_w$ portions, column 5 is $N_{\text{id}}$ of the higher and lower $\sigma_w$ portion, column 6 is the cloud (CAS) LWC of the higher and lower $\sigma_w$ portions, column 7 is the drizzle LWC (CIP) of the higher and lower portions, column 8 is the mean $W$ for the higher and lower $\sigma_w$ portions, and column 9 is the durations of the higher and lower $\sigma_w$ portions of each adjacent cloud pass.

<table>
<thead>
<tr>
<th>Date</th>
<th>$H \sigma_w$ (cm s$^{-1}$)</th>
<th>$L \sigma_w$ (cm s$^{-1}$)</th>
<th>$N_c$ (H–L) (cm s$^{-1}$)</th>
<th>$N_{\text{id}}$ (H–L) (cm s$^{-1}$)</th>
<th>$L_c$ (H–L) (g m$^{-3}$)</th>
<th>$L_d$ (H–L) (mg m$^{-3}$)</th>
<th>$W$ (H–L) (cm s$^{-1}$)</th>
<th>Dur (H–L) (s)</th>
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<td>15 Jul</td>
<td>16.2</td>
<td>15.2</td>
<td>340–213</td>
<td>414–269</td>
<td>0.26–0.31</td>
<td>0.09–0.40</td>
<td>0.34–1.59</td>
<td>235–125</td>
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<tr>
<td>18 Jul</td>
<td>24.1</td>
<td>15.7</td>
<td>387–158</td>
<td>573–226</td>
<td>0.15–0.25</td>
<td>0.38–3.69</td>
<td>−0.92–0.94</td>
<td>67–393</td>
</tr>
<tr>
<td>19 Jul</td>
<td>17.7</td>
<td>14.6</td>
<td>370–110</td>
<td>596–175</td>
<td>0.42–0.45</td>
<td>3.29–5.87</td>
<td>0.29–0.27</td>
<td>120–180</td>
</tr>
<tr>
<td>19 Jul</td>
<td>18.6</td>
<td>15.6</td>
<td>330–110</td>
<td>524–205</td>
<td>0.27–0.28</td>
<td>4.30–10.37</td>
<td>2.20–0.47</td>
<td>102–228</td>
</tr>
<tr>
<td>19 Jul</td>
<td>22.1</td>
<td>17.4</td>
<td>238–104</td>
<td>413–222</td>
<td>0.17–0.18</td>
<td>4.21–12.15</td>
<td>−0.75–0.33</td>
<td>143–247</td>
</tr>
<tr>
<td>19 Jul</td>
<td>12.3</td>
<td>10.1</td>
<td>204–132</td>
<td>388–192</td>
<td>0.33–0.30</td>
<td>3.72–12.04</td>
<td>−0.13 to −0.23</td>
<td>420–180</td>
</tr>
<tr>
<td>19 Jul</td>
<td>11.3</td>
<td>8.3</td>
<td>168–146</td>
<td>294–200</td>
<td>0.15–0.11</td>
<td>6.53–8.47</td>
<td>−0.07 to −0.33</td>
<td>360–330</td>
</tr>
<tr>
<td>20 Jul</td>
<td>15.6</td>
<td>12.6</td>
<td>214–143</td>
<td>268–212</td>
<td>0.20–0.21</td>
<td>2.09–4.80</td>
<td>0.79–0.62</td>
<td>173–127</td>
</tr>
<tr>
<td>20 Jul</td>
<td>14.7</td>
<td>13.9</td>
<td>310–218</td>
<td>388–282</td>
<td>0.31–0.36</td>
<td>2.30–1.84</td>
<td>−0.17 to −0.09</td>
<td>156–384</td>
</tr>
<tr>
<td>20 Jul</td>
<td>18.7</td>
<td>17.6</td>
<td>313–208</td>
<td>382–281</td>
<td>0.16–0.26</td>
<td>0.01–0.52</td>
<td>2.17–0.22</td>
<td>114–246</td>
</tr>
<tr>
<td>22 Jul</td>
<td>13.6</td>
<td>13.0</td>
<td>336–283</td>
<td>400–342</td>
<td>0.23–0.26</td>
<td>0.03–0.20</td>
<td>−0.70–0.67</td>
<td>169–311</td>
</tr>
<tr>
<td>22 Jul</td>
<td>14.2</td>
<td>11.6</td>
<td>283–203</td>
<td>344–333</td>
<td>0.10–0.25</td>
<td>0.02–0.34</td>
<td>−0.33–0.37</td>
<td>443–217</td>
</tr>
<tr>
<td>Mean</td>
<td>16.6</td>
<td>13.8</td>
<td>291–169</td>
<td>415–245</td>
<td>0.23–0.27</td>
<td>2.25–5.06</td>
<td>0.74–0.40</td>
<td>208–247</td>
</tr>
<tr>
<td>Std dev</td>
<td>3.84</td>
<td>2.82</td>
<td>70–56</td>
<td>102–55</td>
<td>0.09–0.09</td>
<td>2.19–4.67</td>
<td>0.73–0.53</td>
<td>128–91</td>
</tr>
</tbody>
</table>
shows how \( L_d \) is associated with lower mean \( W \) in POST, but again mean \( W \) has no associations in MASE. Row 5 shows that lower within-cloud \( \sigma_w \) may promote \( L_d \) in both projects. Row 6 shows that below-cloud \( L_d \) (measured at the same locations and times as the CCN measurements) is well correlated with within-cloud \( L_d \) in both projects. Row 7 shows that \( \sigma_w \) measured at the CCN measurement locations and times is related to \( \sigma_w \) measured within cloud in POST but not in MASE. Row 8 shows that in both projects \( L_d \) below cloud is nearly as negatively correlated with cloud droplet concentrations as is \( L_d \) within cloud (row 1). Row 9 shows that below-cloud \( \sigma_w \) is negatively correlated with below-cloud \( L_d \) in MASE but not in POST. This indicates the differential latent heat release effect on dynamics suggested by Jiang et al. (2002) and Ackerman et al. (2004) in MASE but not in POST.

On the other hand Fig. 18 verifies this below-cloud negative \( L_d - \sigma_w \) relationship in POST if only the 6 cases with substantial drizzle are considered (\( L_d > 5 \text{ mg m}^{-3} \)) or the 10 cases with relative humidity (RH) less than 88.5% where the CCN were measured. There should be more significant evaporation where RH is lower. Furthermore, if only the 19 cases with \( \sigma_w \) greater than 40 cm s\(^{-1}\) are considered \( R = 0.33 \) for \( L_d^\text{CCN} - \sigma_w^\text{CCN} \). Rows 10 and 11 of Table 11 show that drizzle is negatively related to \( N_{CCN} \) in POST but positively related to \( N_{CCN} \) in MASE. Rows 12 and 13 of Table 11 show that \( \sigma_w \) within and below cloud are related to \( N_{1\%} \) in POST but not in MASE. Figure 17 shows that similar \( R \) values are found for \( \sigma_w \) with \( N_{CCN} \) at all \( S \) in both projects. Evidence of this differential drizzle evaporation effect as a cause of the coupling between \( \sigma_w \) and \( N_{CCN} \) in POST is not substantial. Although there is significant evidence that differential drizzle evaporation causes differential below-cloud \( \sigma_w \) in MASE, it is not due to \( N_{CCN} \) but rather to within-cloud \( \sigma_w \) that inversely promotes \( L_d \), that is, low \( \sigma_w^\text{cld} \) promotes lower \( N_c \), greater MD, and \( \sigma_w \), which promote \( L_d \). Consistent with this,
Table 10, column 7, shows greater drizzle in 11 of the 12 divided cloud penetrations for the divisions with lower \( \sigma_w \). The one exception (20 July middle) has the second-smallest \( \sigma_w \) difference and the smallest \( L_d \) percentage difference. There is a factor of 2 greater mean drizzle for the lower \( \sigma_w \) divisions of MASE (Table 10, column 7) as well as for the lower \( W \) divisions of POST (Table 9, column 8) even though half of the six POST cases show greater drizzle in the higher \( W \) divisions (by small margins).

Another theory that would connect \( \sigma_w \) with \( N_{CCN} \) stems from the realization that smaller cloud droplets evaporate more readily (Xue and Feingold 2006; Jiang et al. 2002; Zuidema et al. 2008; Xue et al. 2008); some evidence of this in the RICO experiment was presented by Hudson et al. (2009). The resulting greater latent heat exchange of the greater evaporation in more polluted clouds adds TKE and buoyancy gradients that can enhance \( W \), mixing, and entrainment (Blyth et al. 1988; Zhao and Austin 2005). The stronger \( W \) in the more polluted clouds can also lead to more horizontal motions, and this can further enhance evaporation of droplets, which thus further enhances latent heat exchange and vertical motions, thus, positive feedback. However, these cloud modeling simulations were applied to clouds of a more cumulus nature than the stratuscumuli of POST and MASE, especially MASE, which was more stratus than stratuscumulus, that is, more solid. At any rate, it might be possible that the \( W-N_{CCN} \) and \( \sigma_w-N_{CCN} \) coupling in POST is due to greater latent heat exchanges in the more polluted stratus. This could also include latent heat released during condensation (Lee and Feingold 2010; Storer and van den Heever 2013), which is more rapid for the greater surface areas of the smaller more numerous droplets of more polluted clouds. Especially for stratus clouds, these differential latent heat theories imply a positive relationship between cloud \( \sigma_w \) and \( N_{CCN} \) rather than \( W \) and \( N_{CCN} \). This is a suggestion of greater turbulence in polluted stratus that could result from the greater latent heat exchanges when there is greater \( N_{CCN} \) and \( N_c \).

Figure 17 shows positive \( R \) for all \( \sigma_w-N_{CCN} \) in POST. This includes not only \( \sigma_w \) measured within the cloud passes but also \( \sigma_w \) measurements at two different sets of below-cloud locations, the same places and times where and when the presented CCN measurements were made and over longer distances and time periods that include those of the CCN measurements. It might be notable that the \( R \) values for within-cloud \( \sigma_w \) measurements with \( N_{CCN} \) exceed \( R \) of the below-cloud \( \sigma_w \) measurements with \( N_{CCN} \) at low \( S \) that are more characteristic of the \( S_{eff} \) of the more polluted clouds, which should have the greater latent heat exchanges. Higher \( R \) for within-cloud \( \sigma_w \) with \( N_{CCN} \) than below-cloud \( \sigma_w \) with \( N_{CCN} \) might be expected for this process, although the increased turbulence because of higher \( N_{CCN} \) might be efficiently imparted to below-cloud air in such shallow boundary layers. As should be expected, mean \( \sigma_w \) of POST was 29% higher in-cloud than below cloud at the CCN locations and 12% higher than the more extensive below-cloud \( \sigma_w \) measurements—that is, greater turbulence within clouds. Also to be expected the standard deviation (std dev) and relative std dev of the within-cloud \( \sigma_w \) was greater than the below-cloud \( \sigma_w \) measurements, that is, greater turbulence within clouds. Low \( R \) values such as shown in Fig. 17 are sometimes scoffed, but the significance level (sl) for the 34 POST data points is \(~98%\) for the low \( S \) \( \sigma_w-N_{CCN} \) and \( >85%\) at high \( S \).

The only positive \( \sigma_w-N_{CCN} \) \( R_s \) in MASE are at low or the standard deviation of \( \sigma_w \), which includes the standard deviation of \( S_{eff} \) at high \( N_{CCN} \) just as \( N_c \) does not seem to continue to increase at high \( N_{CCN} \) (i.e., Fig. 5c; roll off).

8. Conclusions

Results of two contrasting stratus cloud airborne field experiments (POST and MASE) reveal the following characteristics that may or may not be universal. Stratus cloud supersaturations \( S_{eff} \) decrease with higher CCN concentrations \( N_{CCN} \) as predicted by T59 (Fig. 13). In clean marine air (i.e., \( N_{CCN} < 200 \text{ cm}^{-3} \)) \( S_{eff} \) often exceeded 1%. In polluted stratus (\( N_{CCN} > 700 \text{ cm}^{-3} \)) average \( S_{eff} \) was \(~0.1%\). This indicates that much smaller particles (i.e., 20 nm) than conventional wisdom (>60 nm) can nucleate stratus cloud droplets (H10), especially in cleaner air masses, which are more susceptible to IAE (Platnick and Twomey 1994). Thus, more numerous smaller particles are capable of inflicting IAE.

Stratus cloud droplet concentrations \( N_c \) increase with \( N_{CCN} \) up to at least \( N_{CCN} = 400 \text{ cm}^{-3} \) above which there is a roll off of \( N_c \) with further \( N_{CCN} \) increase (Fig. 5, Table 6, column 3). Roll off of \( N_c \) with various aerosol measurements other than CCN has been observed by Raga and Jonas (1993), Martin et al. (1994), Twyoh et al. (2005), and Lu et al. (2007; 2008) but not by Bowers et al. (2000). This roll off of \( N_c \) with \( N_{CCN} \) then tends to limit IAE. Vertical velocity \( W \) or the standard deviation of \( W \) \( (\sigma_w) \) have a secondary positive effect on \( N_c \) that became the primary effect on \( N_c \) at high \( N_{CCN} \). T59 showed that differences in the slope \( k \) of CCN spectra might account for the greater–overwhelming \( W \) or \( \sigma_w \) influence on \( N_c \).
at the high \(N_{ccn}\) of MASE. Although Fig. 1b shows no significant differences in mean \(k\) between POST and MASE, Fig. 13 shows large differences in cloud effective \(S\) (\(S_{\text{eff}}\)) between the two projects. At the lower \(S_{\text{eff}}\) of MASE there is higher \(k\) than \(k\) at the higher \(S_{\text{eff}}\) of most of POST. Although \(k\) is just as high at low \(S\) in POST, \(S_{\text{eff}}\) in POST was seldom so low. Thus, in POST the low \(k\) values at high \(S\) are the most relevant for determining cloud microphysics (i.e., \(N_c\)). The low \(S_{\text{eff}}\) forced by the higher \(N_{ccn}\) of MASE makes irrelevant the lower \(k\) values observed at high \(S\) that were seldom achieved in MASE. Thus, the high \(k\) values most relevant to MASE reduce the relationship between \(N_{ccn}\) and \(N_c\) and enhance the relationship between \(W\) or \(\sigma_w\) and \(N_c\) (T59).

This reduction of \(N_{ccn}\) and enhancement of \(W\) or \(\sigma_w\) influences seems to occur at smaller \(k\) than predicted by T59. However, T59 did not consider variations in \(k\) over \(S\), which are observed to increase to even higher values at \(S\) lower than \(S_{\text{crit}}\) (Fig. 1). The \(N_{ccn}\) at all \(S < S_{\text{crit}}\) are important for producing \(N_c\). Furthermore, although \(k\) consistently increased with decreasing \(S\), the CCN spectra were different for each flight and each cloud penetration. This makes a more complicated situation than considered by T59.

A coupling of \(W\) (and \(\sigma_w\)) with \(N_{ccn}\) enhanced the correlations of each with \(N_c\). The \(N_{ccn}-\sigma_w\) coupling could be a result of two different responses to different levels of latent heat exchange between clean and more polluted clouds. One effect is through below-cloud differential drizzle evaporation due to drizzle suppression in more polluted clouds. The other process is greater cloud droplet evaporation of smaller polluted cloud droplets. Both of these processes are predicted to preferentially enhance turbulence in more polluted clouds, which can be expressed by \(\sigma_w\). A limited amount of evidence of these effects has been presented for the POST project, which has a greater range of \(N_{ccn}\) and \(N_c\) and displays the \(W-N_{ccn}\) and \(\sigma_w-N_{ccn}\) coupling. These results are consistent with Chen et al. (2012), who found greater \(W\) variance in ship trail clouds than in adjacent natural clouds. Such coupling between CCN and cloud dynamics tends to support effects opposite of conventional IAE (Xue and Feingold 2006); less cloudiness with higher \(N_{ccn}\).

The predominating effect of vertical velocity variations (\(\sigma_w\)) in the MASE polluted clouds precluded positive correlations of any aerosol parameter with cloud microphysics in MASE. However, this does not mean the irrelevance of the aerosol for cloud microphysics because it is the high \(N_{ccn}\) and high \(k\) that produce the conditions where \(\sigma_w\) has so much influence on stratus cloud microphysics. The \(S_{\text{eff}}\) also decreased with \(N_c\) in POST because of the suppression of \(S_{\text{eff}}\) with \(N_{ccn}\). But in the more polluted MASE clouds, \(S_{\text{eff}}\) increased with \(N_c\) because of the lack of correlation between \(N_{ccn}\) and \(N_c\) and the high \(k\) at the relevant \(S\) of the CCN spectra.

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