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

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Airborne measurements are presented from two summertime central California coastal stratus projects Physics of Stratocumulus Tops (POST) in July-Aug. 2008 and Marine Stratus/Stratocumulus Experiment (MASE) in July 2005. A variety of aerosol and cloud microphysics was encountered in POST but MASE was always polluted.

proj	flts	clds	cb (m)	$N_{1\%}$ Mean (cm^{-3})	$N_{1\%}$ min (cm^{-3})	$N_{1\%}$ max (cm^{-3})	N_c Mean (cm^{-3})	N_c min (cm^{-3})	N_c max (cm^{-3})	$N_c/N_{1\%}$ activ. ratio	k @ S_{eff}
POST	15	34	209	268	72	784	190	45	377	0.79	0.52
MASE	9	50	< 100	597	356	914	240	104	411	0.41	0.82

Table 1. Project, number of flights, number of clouds, mean CCN concentrations at 1% S ($N_{1\%}$), minimum $N_{1\%}$, maximum $N_{1\%}$, mean droplet concentrations (N_c), minimum N_c, maximum N_c, activation ratio, slope of CCN spectra at cloud effective supersaturation (S_{eff}).

POST		MASE	
$N_{1\%}$ (cm^{-3})	S_{eff} (%)	$N_{1\%}$ (cm^{-3})	S_{eff} (%)
< 200	1.286		
200-400	0.641	< 500	0.429
> 400	0.200	500-700	0.178
		> 700	0.160

Table 2. Effective supersaturations (S_{eff}) within various $N_{1\%}$ bins for each project.

Cloud supersaturations exceed 1% in clean air. Thus, particles as small as 20nm can produce stratus droplets.

k	$N_{1\%}$	W
0.20	0.90	0.14
0.42	0.82	0.26
0.50	0.80	0.30
0.52	0.79	0.31
0.75	0.72	0.40
0.82	0.71	0.44
1.00	0.67	0.50
2.00	0.50	0.75
3.00	0.40	0.90
4.00	0.33	1.00

Table 4. Exponents of the two main factors that determine N_c by equation (1) from Twomey (1959).

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

Originally there were 38 horizontal cloud passes to be analyzed in MASE. But 12 of these displayed significant abrupt simultaneous differences in N_c and σ_w. Thus, these 12 passes were split so that the new total number of cloud passes analyzed is 50.

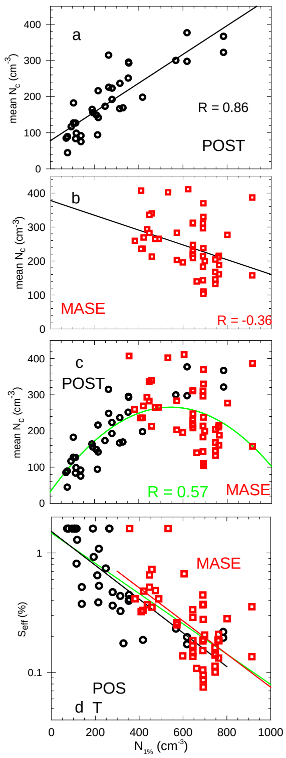

Fig. 1. Mean droplet concentrations (N_c) versus below cloud CCN concentrations at 1% S ($N_{1\%}$) for 34 POST horizontal cloud passes (a) and for 50 horizontal passes in MASE (b). (c) Data from panels a and b together. (d) cloud effective supersaturation (S_{eff}) obtained by matching CCN spectral concentrations, N_{CCN}, with N_c. Linear regressions are shown in a, b, and d, 2nd order regression is shown in c.

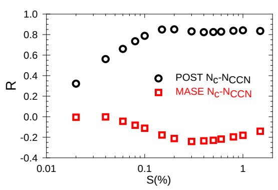

Fig. 2. Correlation coefficients (R) for N_{CCN} at each S with droplet concentrations in both projects. R at 1% are from Figs. 1a and 1b.

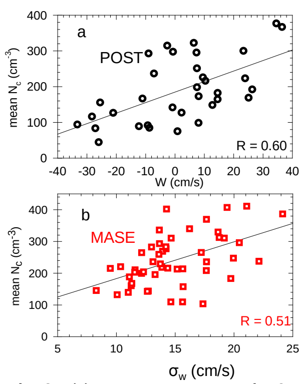

Fig. 3. (a) Mean N_c versus W for 34 POST horizontal cloud passes; (b) mean N_c versus σ_w (sd of W) for 50 MASE horizontal cloud passes. Linear regressions are shown.

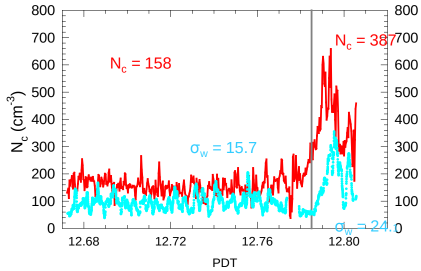

Fig. 4. One second droplet concentration, N_c and σ_w traces with time during one of the 12 divided horizontal cloud penetration during MASE (July 18; Table 3, row 2). Mean N_c, and σ_w for each division are shown.

Often mean W is negligible in stratus so the standard deviation of W (σ_w) is used as a surrogate for W, although this was not the case in POST, it was the case in MASE.

Date	$H\sigma_w$ (cm/s)	$L\sigma_w$ (cm/s)	N_c(H-L) (cm^{-3})
15 July	16.2	15.2	414-269
18 July	24.1	15.7	573-226
19 July	17.7	14.6	596-175
19 July	18.6	15.6	524-205
19 July	22.1	17.4	413-222
19 July	12.3	10.1	388-192
19 July	11.3	8.3	294-200
20 July	15.6	12.6	268-212
20 July	14.7	13.9	388-282
20 July	18.7	17.6	382-281
22 July	13.6	13.0	400-342
22 July	14.2	11.6	344-333
Mean	16.6	13.8	415-245

Table 3. Twelve pairs of adjacent divided cloud passes based on abrupt differences in σ_w and N_c (Fig. 4 is an example). Column 2 is σ_w of the higher σ_w cloud portion, column 3 is σ_w of the lower σ_w cloud portion, column 4 is the mean N_c of the higher and lower σ_w cloud portions.

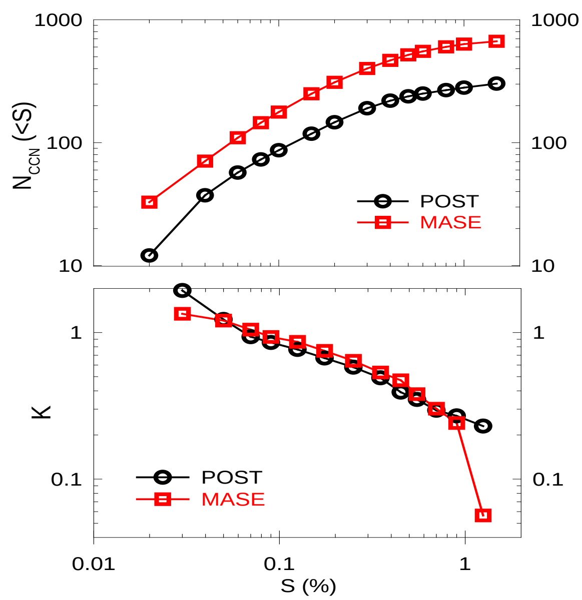

Fig. 5. (a) Mean POST and MASE cumulative CCN spectra. (b) Slopes (k) of these spectra.

Figure 1a displays the positive relationship between CCN concentrations (N_{CCN}) and cloud droplet concentrations (N_c) in POST. This relationship seems to be linear for lower concentrations but then rolls off at high concentrations. Figure 1b for the polluted conditions of MASE shows an extreme roll off to a negative relationship between N_{CCN} and N_c. Figure 1c shows that the combined data seem to display a 2nd order relationship. Figure 2 shows that the positive relationship in POST extends to lower S N_{CCN} and so does the negative R for MASE extend to low S values.

Figure 3 shows the positive influence of cloud dynamics (W or σ_w) on N_c in both projects.

Figure 1d and Table 2 show the decrease of cloud S with higher N_{CCN} that is due to greater competition among droplet for condensate as predicted by Twomey (1959). These show that in clean air cloud S can be more than 1%.

Figure 4 and Table 3 indicate the dominant influence of σ_w on N_c in MASE. In every one of the 12 divided cloud passes N_c is higher in the section with higher σ_w, often very much higher. Since each section of each of these cloud passes probably has the same input CCN, because N_{CCN} did not show as much variability as σ_w, and N_c responded positively to σ_w and there is not a positive R for N_{CCN}-N_c it will be impossible to find any input aerosol parameter that would correlate with N_c in MASE

Twomey (1959) showed that the relative influence of aerosol (N_{CCN}) and dynamics (W or σ_w) depends on the slope (k) of the CCN spectrum. A steeper slope (higher k) reduces the apparent influence of N_{CCN} and increases the apparent influence of W, equation 1 and Table 4.

Twomey (1977) stated;

"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."

Although the CCN spectral shapes of POST and MASE were similar the lower S_{eff} that was forced by the higher N_{CCN} in MASE made irrelvant the low k at high S and made relevant the high k of the lower part of the CCN spectrum, thus making σ_w more important than N_{CCN} for determining N_c as revealed by Figs. 1 and 4 and Table 3.

Apparently this changeover of N_c dependence on N_{CCN} (at low k) to dependence on W(σ_w) at higher k happened at a lower k than predicted by Twomey. The roll off of N_c with N_{CCN} and changeover seem to put limits on the indirect aerosol effect.

Twomey, S., 1959: The nuclei of natural cloud formation, II; The supersaturation in natural clouds and the variation of cloud droplet concentration. *Geophys. Pure. Appl.*, **43**, 243-249.

Twomey, S., 1977: Atmospheric Aerosols. Elsevier Scientific Publishing Company, 302 p.