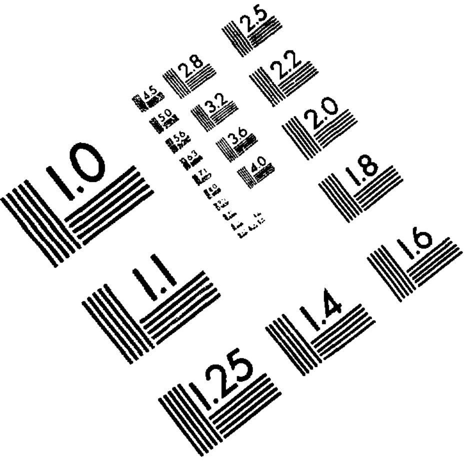

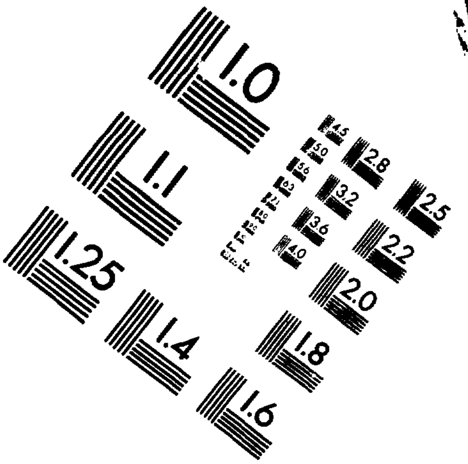

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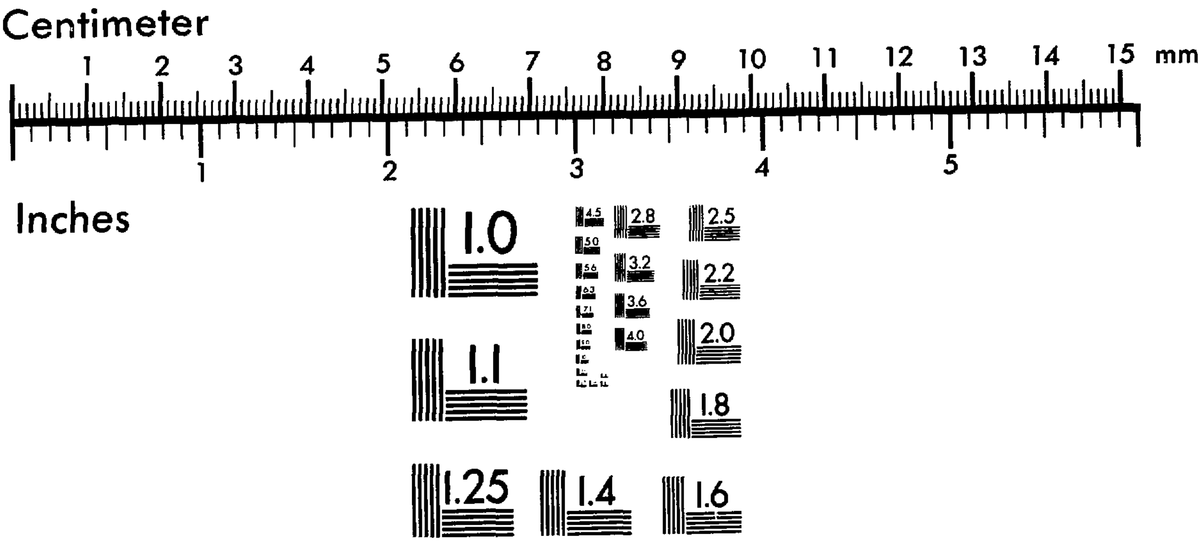

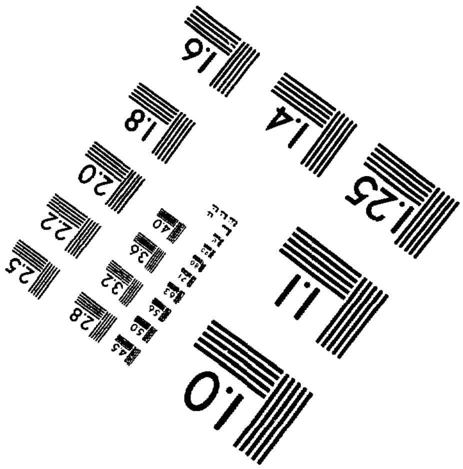

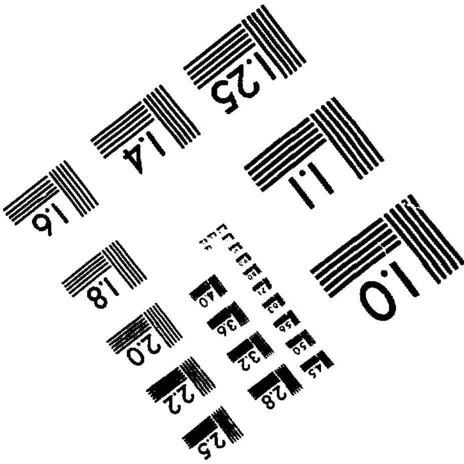

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CLOUD CCN FEEDBACK

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1. INTRODUCTION

Cloud microphysics affects cloud albedo (Twomey, 1977), precipitation efficiency (Albrecht, 1989), and the extent of cloud feedback in response to global warming (Arking, 1991). Compared to other cloud parameters, microphysics is unique in its large range of variability and the fact that much of the variability is anthropogenic. Probably the most important determinant of cloud microphysics is the spectra of cloud condensation nuclei (CCN) which display considerable variability (e.g. Twomey and Wojciechowski, 1969; Radke and Hobbs, 1969; Hudson and Frisbie, 1991a) and have a large anthropogenic component (Hudson, 1991).

When analyzed in combination three field observation projects display the interrelationship between CCN and cloud microphysics. CCN were measured with the Desert Research Institute (DRI) instantaneous CCN spectrometer (Hudson, 1989). Cloud microphysical measurements were obtained with the National Center for Atmospheric Research Lockheed Electra. Since CCN and cloud microphysics each affect the other a positive feedback mechanism can result.

2. RESULTS

Vertical CCN profiles near cumulus clouds (Hawaiian Rainband Project--HaRP-1990) in the mid Pacific were similar to vertical profiles made near stratus clouds in the eastern Pacific (First ISCCP Regional Experiment--FIRE-1987). Figure 1 shows the systematic lower particle concentrations within the boundary layer when clouds were present in the mid Pacific (see Hudson and Frisbie, 1991b Figs. 1 a-d for similar vertical distributions near stratus clouds).

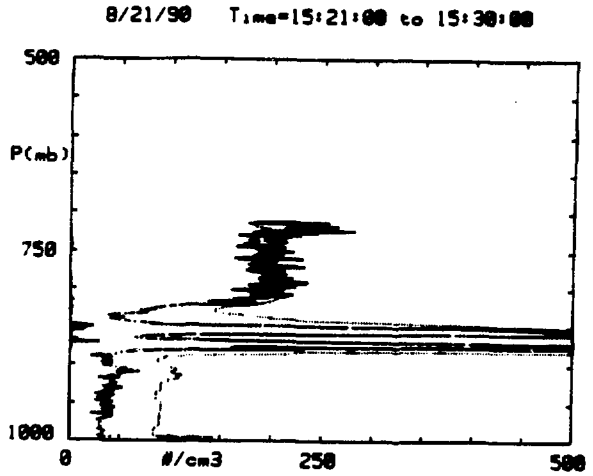

Fig. 1. CCN (dashed line) and CN (dotted line) as a function of pressure altitude near Hawaii. Also shown is the cloud droplet concentration (solid line). Time is GMT.

Figure 2 shows the similarity in concentrations between the boundary layer and the free troposphere when few or no clouds were present (also see Hudson and Frisbie, 1991b, Fig. 1e). The high concentrations measured within the clouds are believed to be artifacts of the sample inlet system (Hudson and Frisbie, 1991b). It is also notable that the CCN concentrations were extremely low near the clouds both above and below (Fig. 3).

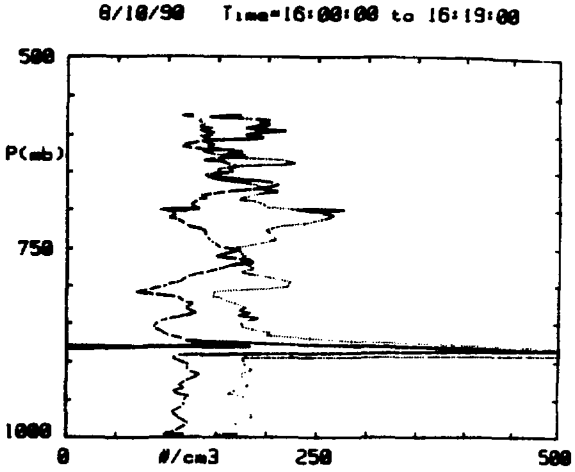

Fig. 2. As Fig. 1 for a "non cloud" situation.

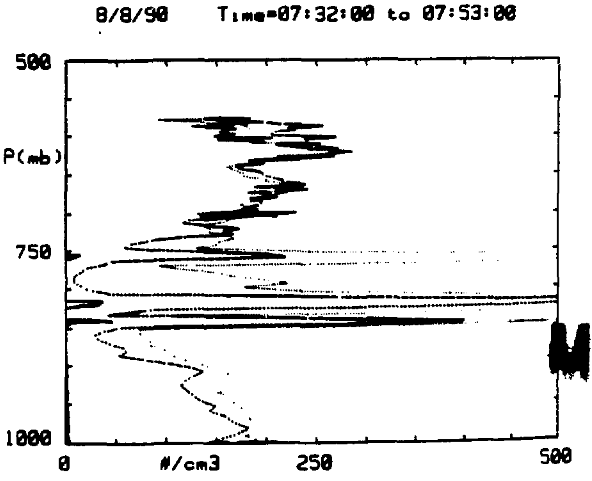

Fig. 3. As Fig. 1.

from Extended Abstracts, 11th Int. Conf. on Clds. and Ppt., Montreal, Quebec, Canada, 17-21 August 1992.

There were two significant differences between the cumulus regime of the mid Pacific and the stratus regime of the eastern Pacific: 1) The layer of high concentrations at the inversion base just above the tops of the clouds which was common in the eastern Pacific (Hudson and Frisbie, 1991b) was much less obvious in HaRP and was often nonexistent. 2) Extremely low particle concentrations, especially CCN, were observed near the cumulus clouds in Hawaii, especially near the tops of the clouds. This was an obscure feature in the stratus regime (Fig. 1b of Hudson and Frisbie, 1991b). Nonetheless relatively low CN concentrations were sometimes observed above the tops of the stratus which indicated a separation between the real high concentrations above the cloud deck associated with high ozone concentrations and the within cloud high concentrations (Hudson and Frisbie, 1991b).

Probably the main reason for difference number 1 was the proximity to continental and anthropogenic particle and trace gas sources. The high ozone layer just above the clouds was also less prominent in HaRP.

The extremely low concentrations observed just above cloud top were also observed in horizontal runs close to the clouds in HaRP. There are several reasons that this feature was quite prominent near Hawaii compared to the eastern Pacific stratus (FIRE): 1) The superior time resolution of the CCN spectrometer in the latter project allowed better spatial resolution. 2) The cumulus clouds have more spatial variability, especially horizontally, which results in more variability in the aerosol. 3) The cumulus clouds have larger cloud drops which lead to more coalescence and thus more coalescence scavenging (Hudson and Frisbie, 1991b) which causes greater reductions in the particle concentrations.

The lower particle concentrations within the boundary layer in both HaRP and FIRE appear to be a result of cloud scavenging processes which are active within the cloudy boundary layer (Hudson and Frisbie, 1991b). In both regimes, stratus and cumulus, the concentrations below the temperature inversion are similar to the concentrations above the temperature inversion when there are few or no clouds present. There appears to be a consistent reservoir of free tropospheric aerosol from which particles can be drawn to the boundary layer. The observations are consistent with this picture which does not require a boundary layer source of particles. In other words it seems rather fortuitous that the boundary layer concentration would match the free tropospheric concentration. If there were a boundary layer source one would expect the boundary layer concentration to sometimes exceed the concentration in the free troposphere.

Table 1 shows microphysical measurements from four sections of cloud in a horizontal flight leg during FIRE. These sections were solid portions of cloud which did not include any holes in the cloud or edge effects. The column N denotes the number of 1 second records used in each cloud section. This shows a progressive decrease in droplet concentration (number cm^{-3}, column labeled fssp) with an increase in the concentration of drops larger than 50 μm (number liter^{-1} column 260X).

TABLE 1

	p (mb)	t	lwc (gm^{-3})	fssp (cm^{-3})	d_m μm	disp. σ/d_m	fssp & d_m corr. coef.	fssp & d_m slope	N	260X (l^{-1})
Flight leg from point A to point B (13:01 - 13:09)										
13:02:30 - 13:04:28										
mean	928.0	10.5	0.28	48.1	18.8	0.26	-0.02	-0.2	119	2.8
std	0.4	0.1	0.05	9.3	0.7					3.6
(std/mean)			18%	14%	4%					
13:04:32 - 13:06:13										
mean	928.1	10.5	0.30	50.6	20.8	0.31	-0.25	-5.4	102	17.5
std	0.3	0.1	0.07	13.2	0.6					17.5
(std/mean)			23%	26%	3%					
13:06:14 - 13:07:19										
mean	928.1	10.4	0.16	29.6	18.8	0.38	-0.34	-1.6	57	34.4
std	0.1	0.1	0.03	4.8	1.0					17.9
(std/mean)			19%	16%	5%					
13:07:51 - 13:08:18										
mean	928.1	10.1	0.24	22.8	22.0	0.45	-0.64	-2.3	28	75.9
std	0.1	0.0	0.05	4.3	1.2					37.5
(std/mean)			21%	19%	5%					

This progression was accompanied by an increase in droplet dispersion and an increase in the magnitude of the correlation coefficient between droplet concentration and median droplet diameter within each section of cloud (the slope of this relationship is also shown). This indicates that on a small scale that lower cloud droplet concentrations are associated with larger droplets and vice versa. Measurements at a lower altitude for the same flight leg (same latitude and longitude) 45 minutes earlier showed a progressive decrease in CCN concentration which was in keeping with the decrease in droplet concentration.

The variations in boundary layer CCN concentrations observed during FIRE by Hudson and Frisbie (1991b) were reflected in cloud droplet concentrations which showed a progressive decrease for the first three flights (June 29, June 30, July 2). The lowest droplet concentrations were observed on July 2 (< 40 cm^{-3}). These were probably a result of decreasing CCN concentrations throughout this period of continuous cloud which resulted in scavenging of particles within the boundary layer. Significantly higher droplet concentrations (~ 100 cm^{-3}) were found for the last two flights, July 16 and 18, when there were much higher boundary layer CCN concentrations. July 18 was unique in that the CCN and CN concentrations did not vary with altitude (Hudson and Frisbie, 1991b, Fig. 1e). As pointed out by Hudson and Frisbie (1991b) this was a broken cloud case with a weak temperature inversion and a short cloud history in the area (there were no clouds in this region on the previous day).

Surface CCN measurements made on board ship in this same area in 1991 were usually similar to the airborne concentrations observed in FIRE. The latter measurements were made between July 8 and July 28 on board the oceanographic vessel Egabrag III during project SEAHUNT (Shiptrail Evolution Above High Updraft Naval Targets) conducted by Dr. William Porch of Los Alamos National Laboratory. However Figs. 4a-b show some extremely low concentrations which were observed for more than 12 hours. This region was characterized by broken low-level clouds that were producing drizzle in spite very little vertical extent. The clouds in this area were often invisible except for the fogbows which could often be observed with the naked eye: at the rainbow angle there was sufficient enhancement of scattered light from the drops to render a visible cloud. These low-level clouds or fogs were also transparent to visible satellite images. The low level clouds did affect the surface solar intensity as shown by the highly variable measurements displayed in Fig. 3b. The solar intensity was notably reduced between 10 and 11 A.M. as the ship passed under a solid cloud line. Coincidentally the CN and CCN concentration increased under this cloud feature. Satellite photos (Hindman et al, 1992) revealed that this was a shiptrail (i.e. Conover, 1966). Twomey et al. (1968) had predicted that these anomalous cloud lines should be visible only where background CCN concentrations were very low (<10 cm^{-3}) as found here. At noon the concentrations returned to normal maritime values as the ship returned to a typical marine stratus regime.

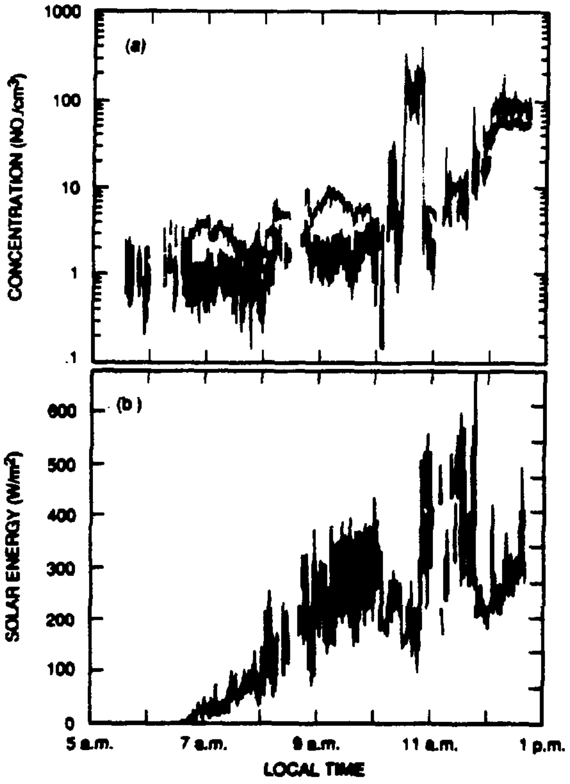

Fig. 4. Surface measurements of (a) condensation nuclei (CN) (light line) and cloud condensation nuclei (CCN) (dark line) concentrations; (b) solar energy as a function of local time off the coast of Baja California on the morning of July 13, 1991.

3. DISCUSSION

Although the CCN concentration was less than 10 cm^{-3} on only this one occasion during the cruise there were several other instances when the CCN concentration briefly showed significant decreases. These episodes were coincident with observations of drizzle on the ship or visible nearby (Fig. 5). Hudson and Frisbie (1991b) suggested that drop coalescence processes can reduce the concentration of CCN because the collection of droplets by drops also reduces the concentration of the nuclei which initiated the individual droplets. This decrease in CCN concentration happens even when the drops evaporate because they leave behind only one nucleus which is composed of the nuclei of the collected droplets.

The lower concentrations observed within the boundary layer in all three projects are probably caused by cloud scavenging processes, especially coalescence scavenging. This process also probably results in the very low concentrations which are often found near the clouds especially in Hawaii (e.g. Fig. 3). The extremely low CCN concentrations found in the vicinity of the shiptrail on July 13, 1991 are probably caused by the extensive drizzle which was prevalent in the area. The low CCN concentrations in turn encouraged the production of larger cloud droplets (i.e. Table 1) which in turn encourages drizzle formation; thus a positive feedback process. The higher CCN concentrations from a ship may have suppressed the coalescence process by increasing the droplet concentrations and thus limiting the sizes of the droplets. The smaller cloud droplets are less likely to collect or be collected by other drops. The lack of coalescence scavenging then left the CCN concentrations intact.

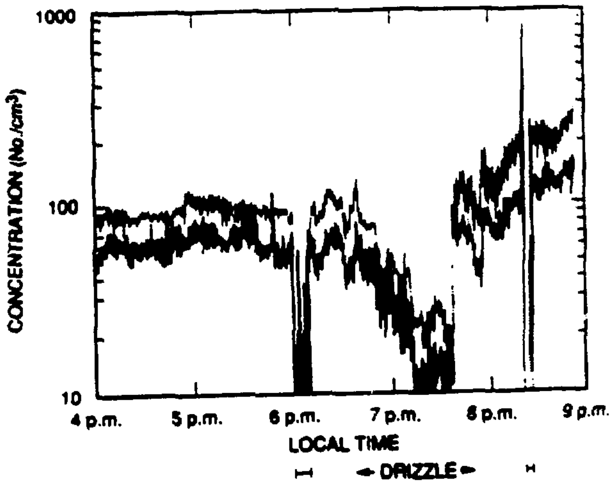

Fig. 5. As Fig. 4a, under a stratus deck on July 18, 1991; concentrations of CN shown as light line, and of CCN as dark line. Bars indicate times when a filter check was in progress.

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