The Microstructure of California Coastal Fog and Stratus

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(Manuscript received 5 November 1976, in revised form 25 July 1977)

ABSTRACT

Detailed vertical profiles of the microphysical properties of West Coast advection fog were made over the San Francisco peninsula during the summers of 1974 and 1975. The sampling platform was the 250 m high Mount Sutro tower which, during much of the summer, protrudes through the coastal marine layer into the subsidence inversion. The microphysical structure was found to vary systematically as a function of air parcel trajectory and air mass history. Maritime trajectories had an average droplet concentration of 89 cm^{-3}, contrasting sharply with continental trajectories averaging 265 cm^{-3}. The effect of nuclei depletion due to washout processes as the air parcels travel through stratus decks was found to reduce the number of nuclei available for condensation by as much as 30%. Despite large variations in their initial structure, each sample displayed a remarkable consistency in its microphysical development. Over the peninsula, the mean droplet diameter and liquid water content increased with height in every case. Without exception, broader drop size distributions were observed near the inversion interface; the distribution also broadened throughout the entire layer during the onshore portion of the fog history. In all cases drizzle drops formed in the uppermost portions of the stratus layer which precipitated downward with time.

1. Introduction

This paper discusses the microphysical data obtained during the sampling of six advection fog cases which occurred over the San Francisco peninsula during the summers of 1974 and 1975. The observation site was the 250 m high Mount Sutro TV tower (Fig. 1), which is located atop a 250 m hill in the center of San Francisco. The Pacific Ocean lies 4.8 km to the west and the Golden Gate Bridge 4.9 km to the north. During much of the summer, the tower protrudes through the coastal marine layer into the capping subsidence inversion maintained by the semi-permanent Pacific High. This makes the tower an ideal platform for detailed studies of the vertical structure of atmospheric parameters. The tower was instrumented at six levels, approximately 40 m apart, by the Department of Meteorology, San Jose State University, for continuous sampling of dry and wet bulb temperatures, pressure, and the u, v and w components of the wind.

The stratus or fog sampled by this project was that portion of the coastal stratus advected onshore during the late afternoon by the strong thermal gradient established as the afternoon heating cycle intensified the thermal low over the central valley. In contrast to fog studies conducted over the open ocean (Mack *et al.*, 1974, 1975), the structure and internal dynamics of the fog in this study were altered by at least two mechanisms. First, once over land, the stratus must rely on the prevailing westerly flow and maritime advection as its primary moisture source rather than the ocean surface itself. Second, the combined effects of terrain and a strong capping inversion act to concentrate the stratus into the uppermost portions of the marine layer accenting the effects of the inversion interface interactions. The terrain cross section, which parallels the coastline, is illustrated in Fig. 2. The rise in terrain (150 m in the final 2 km) creates an updraft averaging 15–20 cm s^{-1} in marine air at the tower site. The observed height differences in the inversion base between the coastline and the tower are generally no more than 80 m.

Microphysical samples were collected manually on the tower at regular intervals throughout each fog case. Prior to the presence of the fog on the peninsula microphysical sampling included 1) sea salt particle measurements at the ground and at the sixth level using Casella cascade impactors, 2) condensation nuclei measurements taken hourly at the ground and at the six level using Gardner Inc. condensation nuclei (CN) counters, and 3) cloud condensation nuclei (CCN) samples taken continuously at 0.5% supersaturation with hourly supersaturation profiles taken between 0.2 to 3% using a Mee Industries Inc. diffusion chamber Model #130. When the stratus or fog stabilized at any level, droplet size distributions were taken with a cloud droplet sampler developed by the Department of Atmospheric Sciences, University of Wyoming. Droplet samples were taken at periodic intervals and at representative levels throughout the fog life cycle to obtain the variation in the drop size distribution with height and time. The CN and CCN counters and the Casella impactors continued to operate for 2–3 h after the fog dissipated.

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Fig. 1. Mount Sutro TV tower.

2. Synoptic and micrometeorological structure

All of the cases sampled were obtained during periods of widespread coastal stratus. Although there were rather large variations in the synoptic pattern among the cases, the micrometeorological structures were surprisingly similar. The average fog temperature observed during 1974 ranged from 10 to 14°C while those observed in 1975 ranged from 8 to 11°C. The vertical temperature profile in all cases was nearly isothermal. The total nocturnal cooling at the top of the marine layer varied from 1 to 3°C, the greatest cooling rate occurring just after the onset of fog. The mean wind speed varied from 3 to 10 m s^{-1} in the marine layer, reaching a maximum between 1600 and 1800 PST, at the time the fog was advected over the peninsula. The speed reached a minimum during the early morning hours. The diurnal oscillation of wind varied with height above the tower base and among the fog cases. The flow in the marine air varied between 270° and 220°, with the westerly flow observed during the late afternoon changing to southwesterly after midnight. Northwest flow predominated above the inversion base. Within the marine air the vertical wind component averaged $+20$ cm s^{-1}, while within the inversion the velocity was downward. The vertical eddy fluxes of temperature and moisture in the marine air were always very small, usually between -0.01 and $+0.01$ (°C m s^{-1} and g kg^{-1} m s^{-1}); within the inversion, they were generally an order of magnitude greater. A brief summary of the main features of each fog case is given in Table 1 and a detailed discussion of the individual cases can be found in Goodman (1975, 1976).

3. Microphysical data

In contrast to the micrometeorological data, the microphysical structure of the fog cases varied radically from case to case and, on occasion, during the fog life cycle, itself. This seeming inconsistency was resolved after detailed analyses of the synoptic and mesoscale flow revealed discernible differences in the air parcel trajectories and air mass histories. Categorizations according to whether the trajectory was 1) maritime, 2) continental or 3) maritime-continental modified and according to air mass history, could explain the observed nuclei concentration and drop size distributions. The source region is an obvious indication of the initial type and distribution of available nuclei, while the

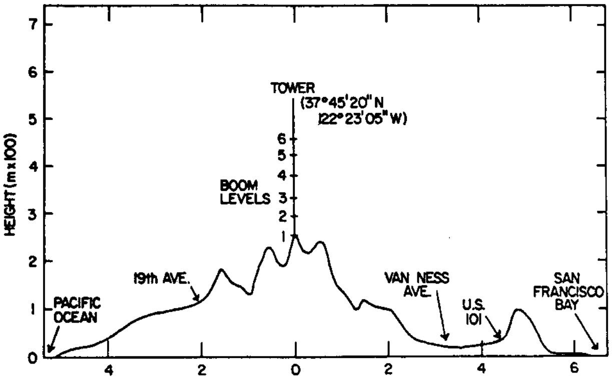

Fig. 2. West-east vertical cross section of the San Francisco Peninsula through the tower site. The vertical scale is greatly exaggerated.

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TABLE 1. Summary of fog features.

Date	Time of fog advection to tower site (PST)	Time of fog dissipation at tower site (PST)	Average fog thickness at tower site (m)	Average temperature range (°C)	Drizzle observed at ground
17–18 July 1974	Fog continuously at tower site for several days; sampling started at 1200.	No dissipation; sampling ended at 1003.	~90	12–14	Yes
20–21 July 1974	1810	1100	~80	10–13	Light drizzle at night
26–27 July 1974	1630	Fog lifted at 1030 and by 1200 no stratus at tower site.	~220	12–14	Light drizzle
6–7 August 1974	0130	0900	~160	10–11	No
12–13 July 1975	1730	0915	~220	8.5–11	No
4–5 July 1975	Fog continuously at tower site for several days; sampling started at 1447	No dissipation; sampling ended at 1050.	>220	8–9.5	Light drizzle

TABLE 2. Trajectory grouping and summary of microphysical parameters.

Date	Height above tower base (m)	Distance in coastal stratus prior to arrival at SFO (n mi)	Average mean diameter (μm)	Percentage of droplets <10.2 μm	Percentage of droplets <14.7 μm	Average LWC (g m^{-3} $\times 10^{-2}$)	Concentration (cm^{-3})	Average concentration (cm^{-3})	Number of samples
Maritime trajectories									
17–18 July 1974	2	50–60	7.3	76.6	98.4	3.8	88	88.6	11
	53		7.1	71.5	96.3	3.89	79		11
	111			87.7	99.5	2.62	99		1
Maritime-continental modified trajectories									
4–5 August 1975	53	200–220	5.1	100.0	100.0	0.99	148	143.2	11
	111		5.4	99.9	100.0	1.26	153		11
	162		5.2	99.8	99.9	1.09	146		9
	225		5.2	99.8	100.0	.93	126		1
20–21 July 1974	2	100–120	6.1	80.2	97.9	5.21	145	169.6	12
	53		7.9	75.1	97.9	7.98	180		11
	111		9.0	60.4	97.1	11.31	184		2
12–13 July 1975	53	10–20	5.4	98.9	99.9	1.89	225	208.4	8
	111		5.4	99.4	99.9	1.59	192		5
	162		6.3	96.6	99.5	3.78	260		4
	225		6.8	96.8	99.6	2.58	156		3
Continental trajectories									
26–27 July 1974	2	100–150	7.0	94.6	99.5	4.17	194	214.5	4
	53		5.9	96.7	99.7	4.27	244		5
	111		7.5	91.9	99.2	6.77	231		8
	162		8.2	83.7	99.3	9.68	251		4
	192		8.0	91.4	98.9	7.77	226		2
	225		10.0	58.9	92.8	10.12	141		6
6–7 August 1974	2	No satellite data available	4.5	99.2	100.0	0.86	306	316.5	1
	53		4.9	97.5	99.5	2.80	254		4
	111		5.8	96.8	99.2	5.56	306		6
	162		7.5	95.7	99.3	10.73	400		1

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history reveals periods of nuclei filtering and possible washing in stratus decks. Fig. 3 shows the 72 h trajectories of 17–18 July 1974 categorized as a maritime trajectory; of 26–27 July 1974 and 6–7 August 1974 categorized as continental trajectories; and of 20–21 July 1974, 12–13 July 1975 and 4–5 August 1975 categorized as maritime-continental modified trajectories. Table 2 gives the air mass histories of each case along with the observed drop size distribution, droplet concentration and liquid water content.

a. Drop size distribution

The fog droplet samples were taken with a cloud droplet sampler based on the sampling techniques of Squires and Gillespie (1952). The sampling flow speed was held between 60 and 65 m s^{-1} and the exposure time was on the order of a millisecond so that each sample of droplets comprised a volume of only a few cubic centimeters. The sizes of the craters left by droplets impinging on a soot-coated glass slide are related, by laboratory calibration, to the droplet diameter. The maximum cloud droplet diameter that can be effectively estimated with this sampling device is $\sim 50\,\mu$m (Auer, private communication). The sampling method causes some error, primarily due to the lack of representativeness of the sample. The error is particularly important for small droplets for which the number of replicated droplets is limited by small collection efficiencies, necessitating large corrections (Langmuir and Blodgett, 1946). For the larger droplets the errors arise due to the small sampling volume. Droplet samples were taken every 60–90 min at several levels to obtain the variation with time of the size distribution in the vertical.

The drop size distribution was found to be a function of vertical distance from the inversion base. Typically, the mean and median diameter increased with height, as shown in Figs. 4–6. The selected microscopic photographs taken on 27 July 1974 (Fig. 7) further illustrate this increase with height.

There are a few deviations from this pattern, either because of the unrepresentativeness of the samples as discussed earlier or because they were taken at the fog's edge where evaporation was occurring. The observations also indicate that the drop size distribution broadens with height and time. The broadening with height can be seen in Table 2, which presents for each sampling level average values of mean diameter, liquid water content (LWC), droplet concentration and the percentage of droplets having diameters less than 10 and 15 μm. Even if the dissipation phase is included, when a narrowing would be expected, the overall average still broadened with height. The percentage of droplets less than 10 and 15 μm in diameter decreased with height. The changes in the fog's microstructure as time progressed are illustrated in Fig. 8, which depicts

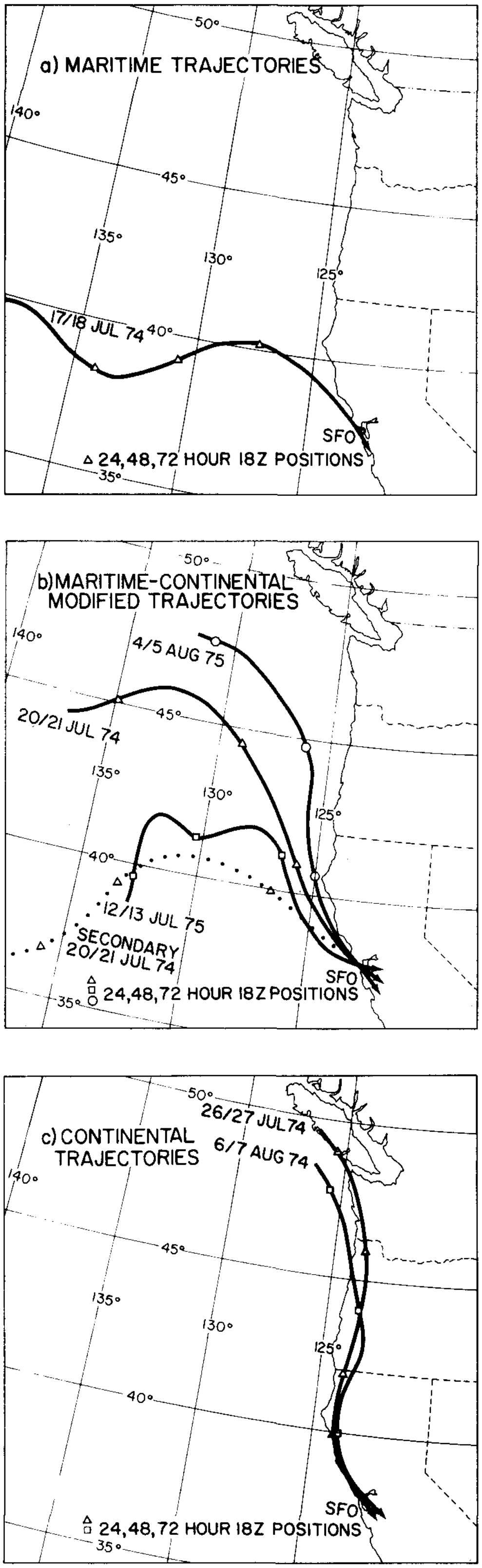

Fig. 3. Air parcel (a) maritime trajectories, (b) maritime-continental modified trajectories and (c) continental trajectories. Positions are shown at 24, 48 and 72 h.

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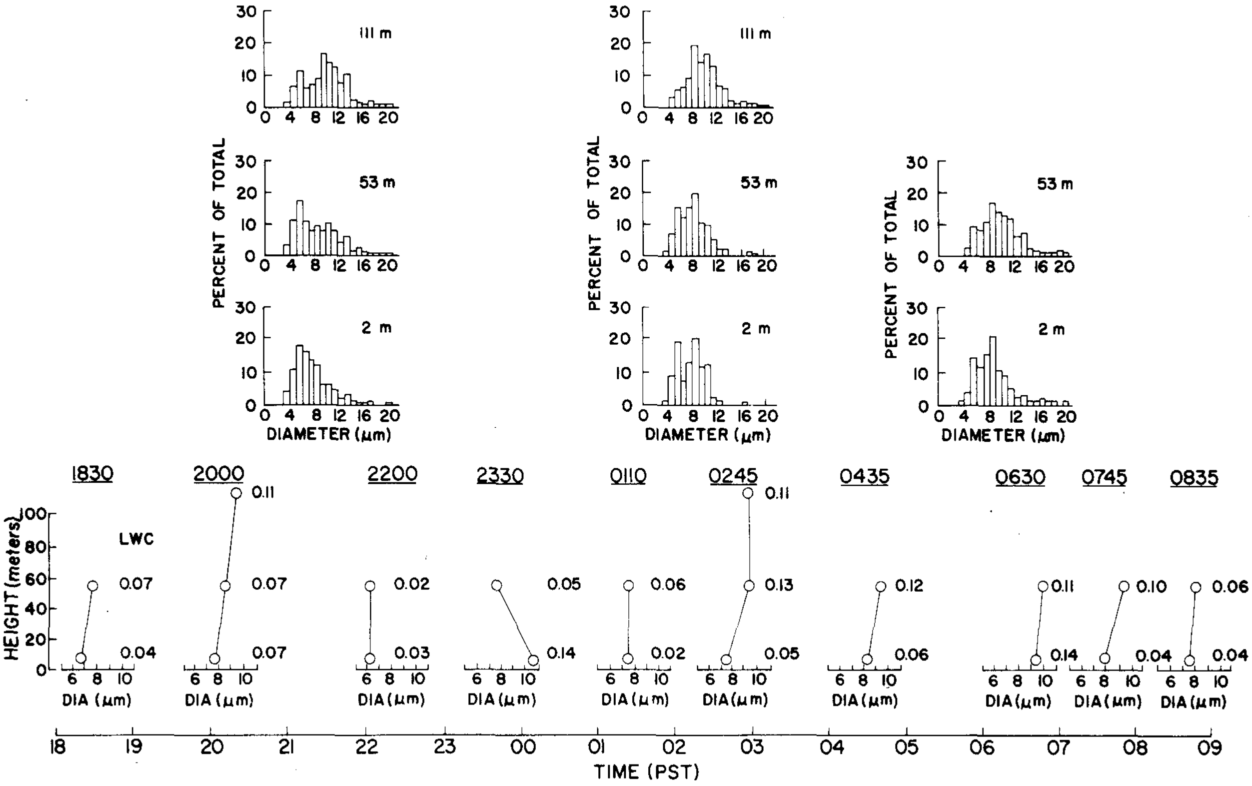

FIG. 4. Vertical profiles of median diameter (bottom) as a function of height for 20–21 July 1974. The numbers on the right side of each profile represent the liquid water content (g m^{-3}). Normalized drop size distributions are shown above some profiles.

the fog life cycle in four quarters: formation, second quarter, third quarter and dissipation. The mean droplet diameter generally increased with time at all levels, reaching maximum values in the third quarter (between 0100–0500 PST) then retreating toward the formation size during the dissipation phase. The dissipation phase for this study was assumed to start at sunrise.

The mean diameter ranged from 4.5 to 10.5 μm which is rather small for California coastal stratus when compared with the values published by Neiburger and Wurtele (1949) and Mack *et al.* (1973, 1974, 1975). This study consistently observed an increase in mean diameter with height, in contrast to the above studies, which generally reported decreasing mean diameters with height. Aircraft samples taken close to San Francisco by Fowler *et al.* (1974) observed narrow size distributions, modal diameters between 7 and 9 μm, liquid water content between 0.02 to 0.52 g m^{-3} and droplet concentrations ranging from 157 to 479 cm^{-3}. These observations, taken just off the coastline, are close to those obtained by this study

The development of drizzle size drops was observed in all cases in the uppermost part of the stratus. It is expected that due to a steady updraft in the marine layer at the tower site and the radiative divergence at the stratus top that the first signs of a coagulation process would be observed there. Later in the fog life cycle, precipitation size drops will settle through the marine layer and in some cases reach the ground. Although this sequence of events was observed in each case, we recorded drizzle rates only at the ground. Therefore no qualitative values of the coagulation process can be given at the present time. The drizzle rate at the ground, determined from the sizes of colored stains left by drops impinging on dyed Whatman No. 1 filter paper, is shown in Fig. 9.

b. Droplet concentration

The droplet concentration varied markedly during individual fog life cycles and radically among fog cases. The concentration ranges from 40 cm^{-3} to as many as 450 cm^{-3}. There was no noticeable trend observed during the fog life cycle or predictable variation with height, except for a pronounced decrease in the uppermost part during the third quarter of the life cycle. The coagulation process was well developed at this time and drizzle quite frequently reached the ground.

Drop size distribution was highly correlated with concentration. Those cases with a high concentration had a relatively narrow spectrum with a well-defined peak and a relatively small mean diameter. This might be expected because the available water vapor must be distributed over more nuclei, allowing no single droplet

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to grow much faster than the mean. During each case, the concentration remained fairly constant, whether relatively high or low. The variation in concentration among cases is attributed to the large variation in the number of available nuclei, as is evident from the 72 h air mass history (Table 2, Fig. 3).

For the 17–18 July 1974 maritime trajectory case, the average concentration varied with height from 79 to 99 cm^{-3}, with an overall average of 89 cm^{-3}. This contrasts sharply with the 6–7 August 1974 continental sample, whose average concentration varied with height from 254 to 400 cm^{-3}, with an overall average of 316 cm^{-3}, and the 26–27 July 1974 continental sample with an overall average of 214 cm^{-3}. When grouped according to trajectory type, the maritime case averaged 89 cm^{-3}, the maritime-continental modified cases 174 cm^{-3}, and the continental cases 266 cm^{-3}. Among the maritime continental modified cases (assuming the source region is the same), nuclei depletion due to washing is apparent. The 4–5 August 1975 trajectory carried the parcels through 200–220 n mi of coastal stratus prior to their arrival at San Francisco, where the overall average droplet concentration was 143 cm^{-3} (Fig. 10). On 12–13 July 1975, however, the main body of coastal stratus was displaced well to the south of Monterey Bay leaving only remnants over the Bays of San Francisco and Monterey (Fig. 11). The resulting "clear air" trajectory resulted in an overall average concentration of 208 cm^{-3}. A similar trend was also observed in condensation nuclei (CN) concentration. The average CN concentration over the sampling period on 12–13 July 1975 was 10 930 cm^{-3} and on 4–5 August, 5100 cm^{-3}. The 20–21 July 1974 sample most closely approximated that of 4–5 August 1975, with a 100–120 n mi trajectory in stratus and overall average droplet concentration of 170 cm^{-3}.

c. *Nuclei observations*

Cloud condensation nuclei (CCN) supersaturation profiles were measured hourly prior to, during and after the fog's presence at the tower. Considering the diffi-

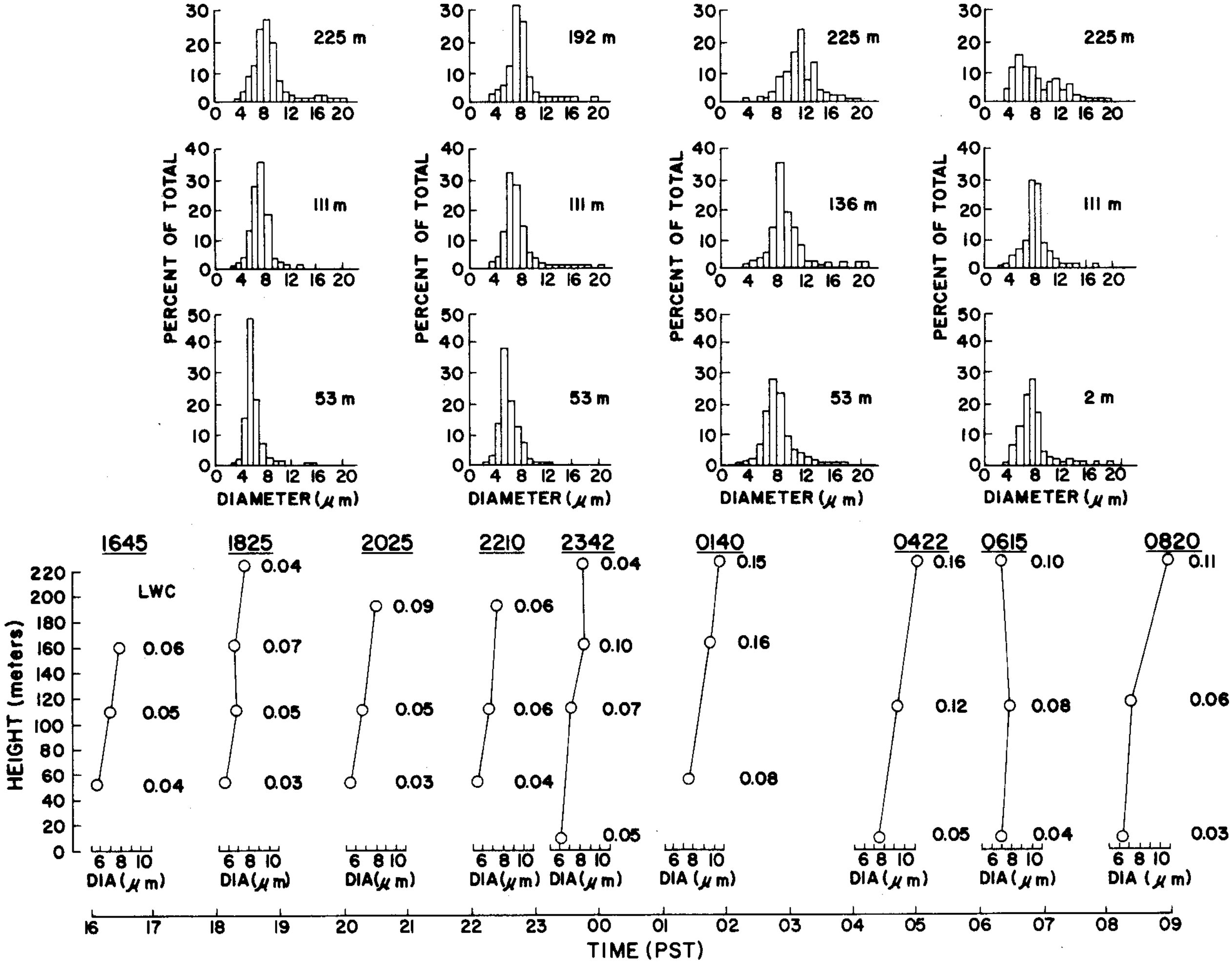

Fig. 5. As in Fig. 4 except for 26–27 July 1974.

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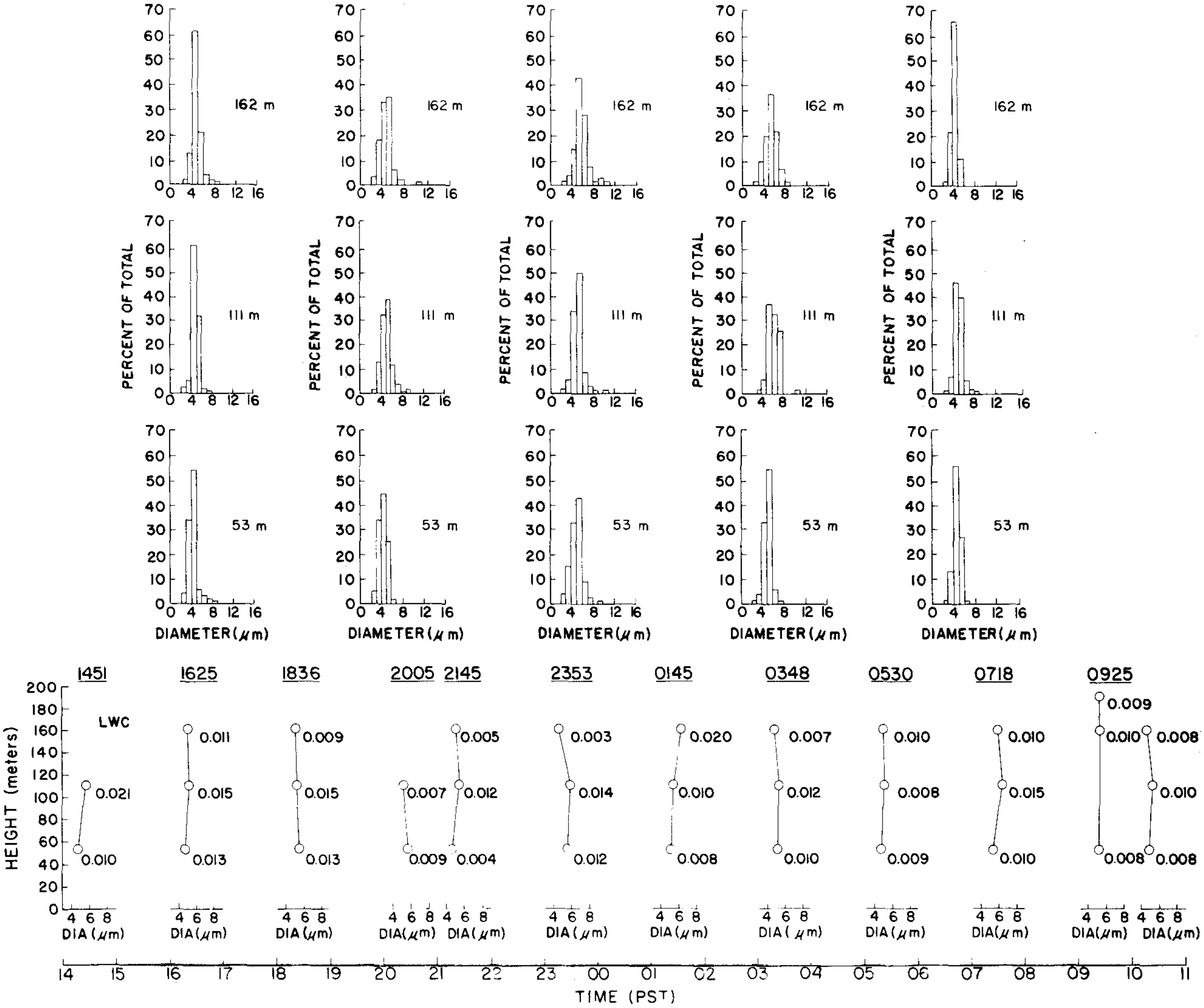

FIG. 6. As in Fig. 4 except for 4–5 August 1975.

culties in the proper interpretation of CCN measurements in high relative humidities (Saxena *et al.*, 1970; Fitzgerald, 1970), our discussion will concentrate mainly on the data gathered prior to and after fog conditions.

Supersaturation spectra, usually based upon measurements at 10–15 different supersaturations, were generally observed to be linear when plotted on a logarithmic scale. A log-log least-squares fit to an expression of the form $N=CS^k$, where N is the number of nuclei per unit volume with critical supersaturation less than S, provided a description of each spectrum in terms of the parameters C and k. The values for C and k are given in Table 3, together with correlation coefficients of the regression. Generally, the slope parameter k remained fairly constant prior to and during the presence of fog with an average value of approximately 0.5. The concentration parameter C decreased slightly during the fog's life as CCN nuclei became activated or were collected by cloud droplets. The observed value of $k\approx0.5$ is comparable to those reported by Twomey and Wojciechowski (1969), Jiusto (1966) and Fitzgerald (1972) for maritime air. The values of C (Table 3) were significantly higher than those reported by other investigators sampling over the open ocean where the concentration parameter is usually less than 50. However, they do agree quite well with those found by Elliott and Egami (1975) (∼400) along the West Coast (Oregon and Washington) with north to northwest winds.

These observations support current continental-marine mixing theories in which mesoscale circulations promote the spread of continental nuclei over the ocean through both vertical and horizontal circulations. In such cases, even totally marine trajectories do not necessarily imply purely marine samples.

As was previously mentioned, CCN counts slowly decreased during the night. The counts on 12 and 13 July increased dramatically after sunrise. There are

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several possible explanations for this increase but a combination of the following two seem most reasonable. First, the fog that was sampled during this period was not typical of widespread west coast advection fog. Rather, the fog sample was localized in extent, being confined to the San Francisco and Monterey Bays with the main body of coastal stratus occurring far to the south of Monterey (Fig. 11). During the early morning hours, without the presence of a large stratus bank offshore, the sample tended to dissipate through evaporation rather than through a slow seaward advection. The air that flowed over the tower after fog dissipation was probably laden with a fresh supply of active nuclei. This evaporation process supports the second mechanism studied by Radke and Hobbs (1969) and Dinger *et al.* (1970). They showed that, in addition to acting as sinks for particles, clouds also provide a medium for the growth of certain chemicals which may be released as particles when the cloud evaporates (Easter and Hobbs, 1974).

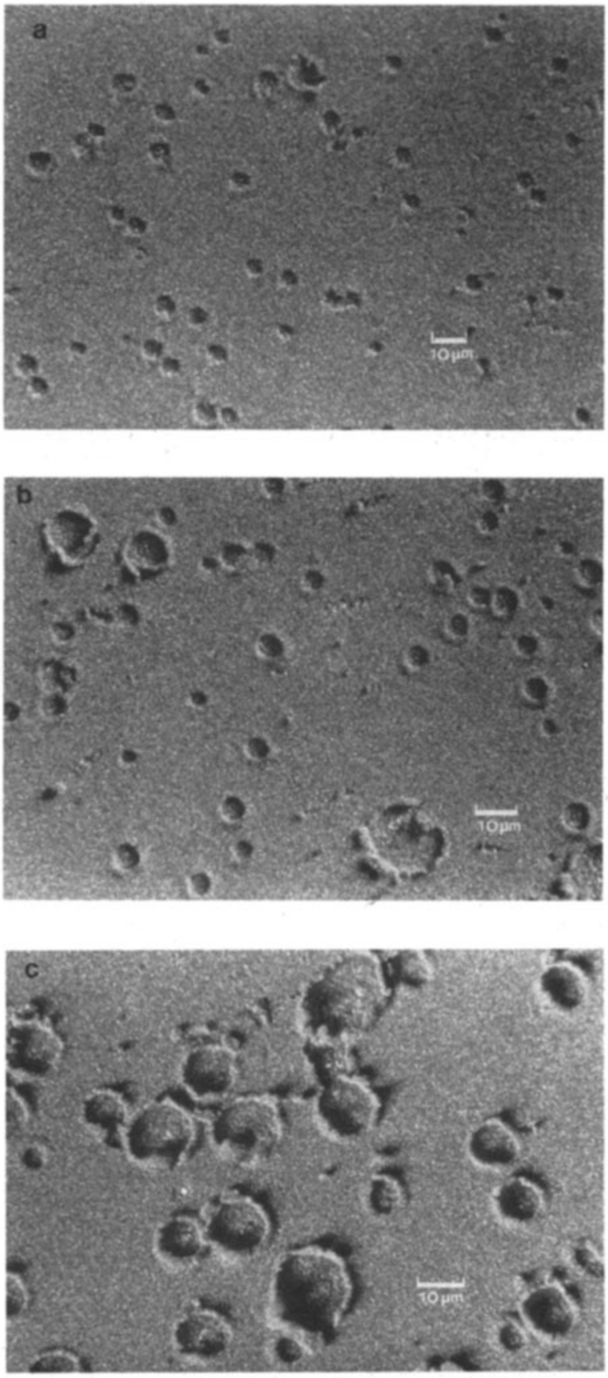

FIG. 7. Microscopic photographs of droplet replicas in soot on 27 July 1974 illustrating the vertical development in drop size distribution: (a) 2 m above tower base at 0830 PST, (b) 111 m above tower base at 0820 PST, (c) 225 m above tower base, close to top of fog, at 0810 PST.

TABLE 3. Cloud condensation nuclei supersaturation profiles based on the expression $N=CS^k$.

Date (1975)	Time (PST)	C	k	Correlation coefficient
12–13 July	1332	733	0.47	0.88
	1517	569	0.43	0.94
	1824	732	0.53	0.97
	1940	722	0.54	0.96
	2039	797	0.42	0.88
	2214	735	0.47	0.89
	2348	648	0.55	0.87
	0116	717	0.64	0.96
	0327	620	0.53	0.98
	0522	534	0.55	0.96
	0609	557	0.45	0.80
	0706	933	0.74	0.99
	0821	1130	0.75	0.98
	0857	1238	0.79	0.97
4–5 August	1635	710	0.48	0.90
	1745	510	0.56	0.97
	1915	557	0.58	0.97
	2030	476	0.53	0.96
	2130	420	0.52	0.96
	2235	385	0.56	0.97
	2345	559	0.49	0.90
	0050	490	0.58	0.98
	0158	483	0.55	0.99
	0320	521	0.52	0.98
	0435	450	0.45	0.96
	0538	549	0.43	0.95
	0656	496	0.34	0.88
	0800	551	0.37	0.85
	0900	456	0.30	0.94

An attempt was made to compute fog droplet concentrations from CCN supersaturations profiles measured prior to the fog's advection using Twomey's equation. The calculated droplet concentrations were about 34–45% higher than those actually measured. Similar correlations were reported by other investigators (Squires and Twomey, 1960; Twomey and Warner, 1967; Fitzgerald, 1972).

Condensation nuclei were sampled hourly at ground level and in the inversion (sixth level). The peak

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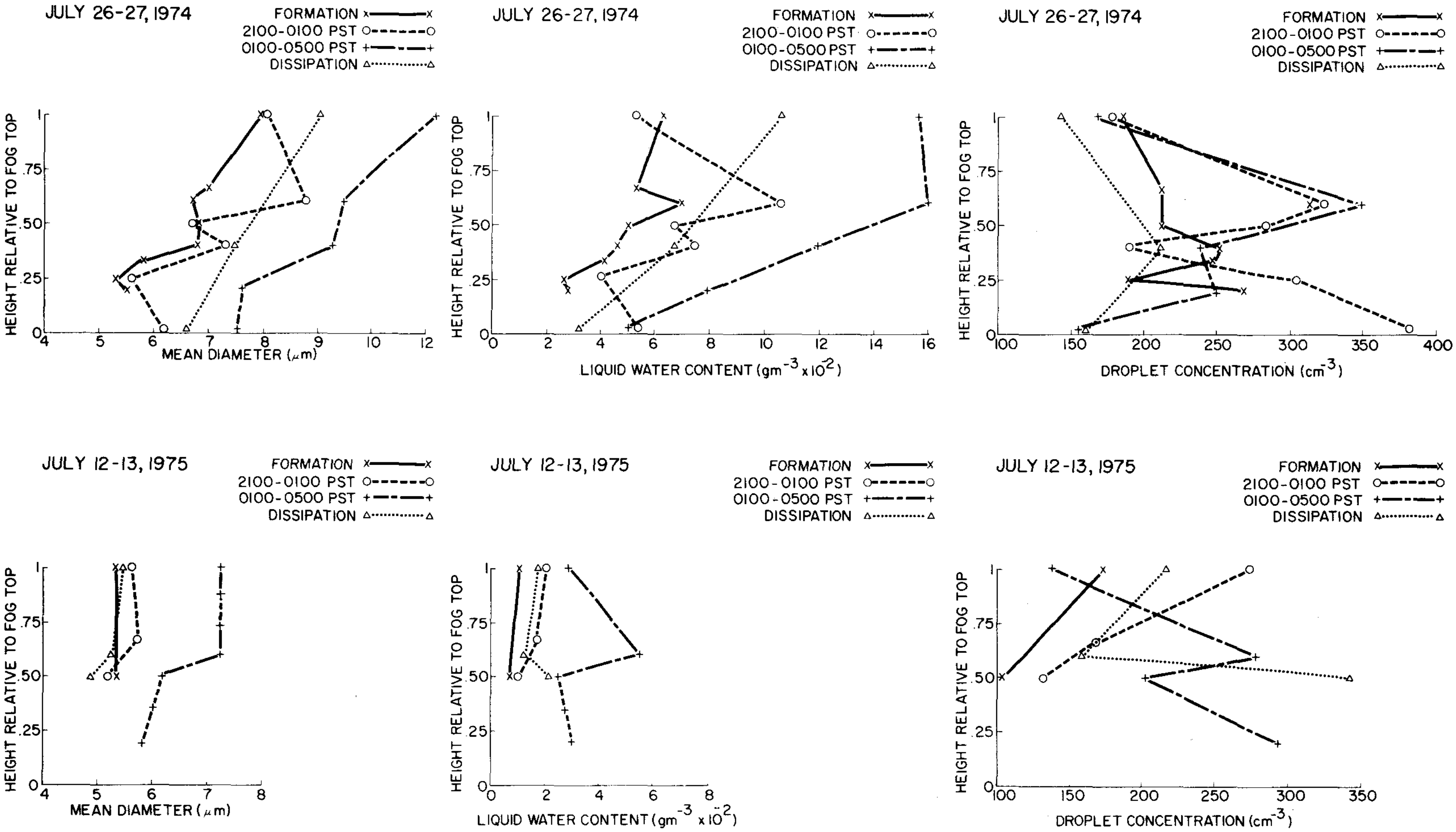

FIG. 8. Vertical profiles of average mean droplet diameters, liquid water content and droplet concentration at fractions of the fog life cycle on 26–27 July 1974 and 12–13 July 1975.

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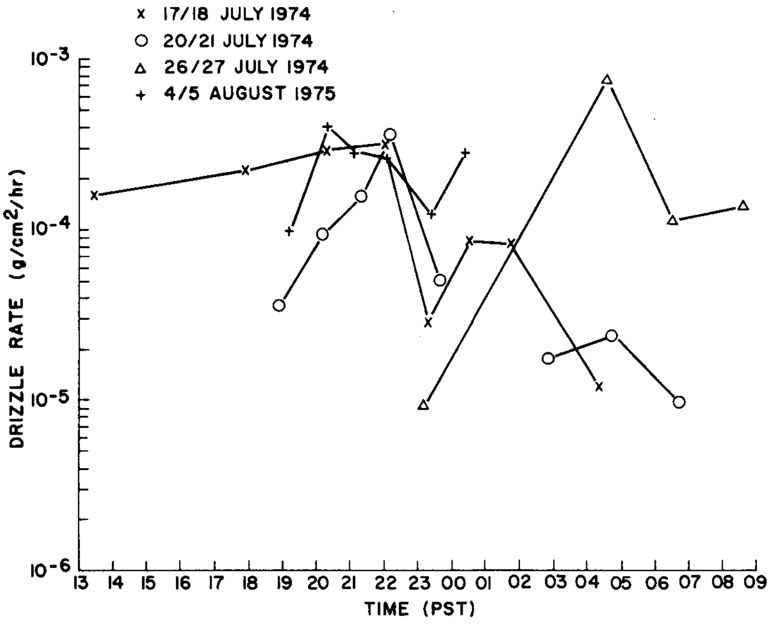

Fig. 9. Drizzle rate [g(cm^{-2} h)$^{-1}$] as function of time for several periods.

concentration (30 000–40 000 cm^{-3}) was observed during the late afternoon and early morning hours. The gradual decrease in condensation nuclei concentration due to scavenging mechanisms in fog was observed through the night. Minimum recorded values were in the range of 1000–2000 cm^{-3}. It is worth noting that the daily variations of CN concentration in the inversion and at the ground are in phase. Even the peaks generated by rush hour traffic coincide at the two levels. This implies a rapid transport mechanism through the inversion, which is discussed in detail by Goodman and Miller (1977).

d. Liquid water content

The liquid water content (LWC) was calculated directly from the drop size distributions. Since the larger droplets are the main contributors to the LWC and the droplet sampler used in this project is ineffective in this range (as discussed earlier), it is expected that our values for LWC are considerably underestimated. Computed LWC ranged from 0.009 to 0.16 g m^{-3}, varying with both time and height in each case. Typically, the LWC increased with height and time (Table 2, Figs. 4, 5 and 6).

4. Discussion and conclusions

The two-year study showed that the microphysical structure of advection fog is largely determined by the influence of synoptic-scale features. The differences appear to be closely related to the trajectory and air mass history prior to their arrival at the sampling site. This results in variations in the available condensation nuclei determined primarily by the source region but also by the amount of nuclei washout.

Maritime (westerly) trajectories generally result in

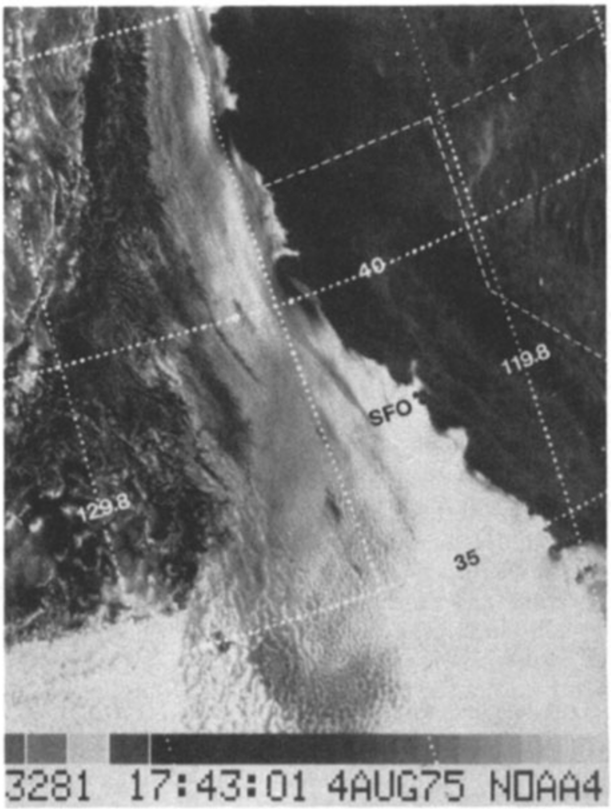

Fig. 10. NOAA 4 West Coast pass on 4 August 1975 (visual, 1743:01 GMT).

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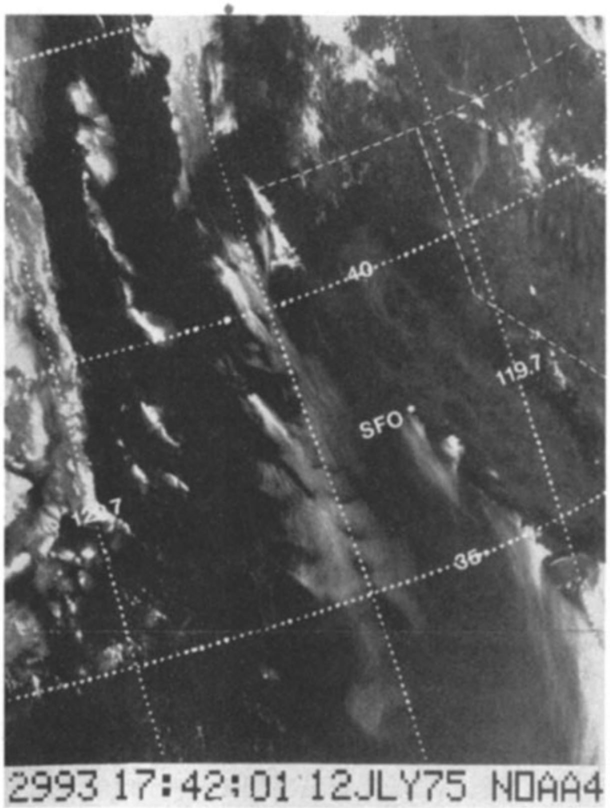

FIG. 11. NOAA 4 West Coast pass on 12 July 1975 (visual, 1742:01 GMT).

low droplet concentrations, large mean diameters and broad drop size distributions. However, maritime trajectories that are modified by continental influences (northwest to north) have higher droplet concentrations, smaller mean diameters and narrow drop size distributions with sharper peaks. The effects of nuclei washout are felt as the trajectories carry the parcels through varying distances of coastal stratus prior to their arrival on the San Francisco Peninsula. During these periods nuclei are depleted as they are activated during the formation of cloud droplets or as they are attached and collected by cloud elements.

Despite large differences in the synoptic flow, there was a surprising degree of similarity in the microphysical development of each case during its life cycle. Each case displayed its own characteristic patchiness, thickness and duration, yet each predictably moved onshore during the period of maximum onshore wind to establish a near-isothermal layer of fog with temperatures ranging from 8 to 11°C in 1975 and 11 to 14°C in 1974. During its presence on the peninsula each case exhibited an increasing mean droplet diameter and LWC with height. Without exception broader drop size distributions were observed near the inversion interface and the entire layer generally broadened during its onshore life cycle. All cases formed drizzle drops in the uppermost portions of the stratus layer which precipitated downward with time.

The consistency with which the fogs evolved during their life cycle implies a rather persistent mechanism leading to growth processes. In stratiform clouds, droplet growth and development are largely contingent on the establishment of a vertical transport mechanism (Mason, 1971). For the lower and middle portions of the stratus layer the vertical-wind-shear-generated eddy turbulence coefficients are on the order of 4–10 $m^2 s^{-1}$. The effects of the local terrain (rising 150 m in the final 2 km) acted to compress the stratus into the uppermost portions of the marine layer while generating a relatively smooth updraft through the entire layer averaging 15 cm s^{-1}. The forced interaction of the upper stratus layer with the inversion interface is felt to be the dominant dynamic mechanism for droplet development in the region. Current studies by Miller (private communication) and visual observations by the investigators on this project confirm the presence of a well-developed wave structure at the interface with amplitudes and wavelengths averaging 20 and 250 m, respectively. The reflection of this motion into the stratus structure can be expected to support transport to a depth equal to or greater than the amplitude of the wave at the interface (Goodman and Miller, 1977).

A second and potentially important process is active at the inversion interface. Condensation nuclei and sea-salt particle measurements (Goodman, 1975, 1976) taken simultaneously below and above the inversion show that particle penetration "through" the inversion occurs regularly and with remarkable ease. The implication that the two environments are systematically mixed suggests an additional mechanism for droplet development. Large fluctuations in liquid water content in the upper portion of the marine layer could act to speed droplet growth through an enhanced coagulation process as described by Twomey (1976). The dynamics of this transport mechanism through inversion is currently under investigation (Goodman and Miller, 1977), but its implication to cloud physics is far from being completely understood.

Acknowledgments. The author acknowledges support from the National Science Foundation under Grant GA-42464 and the Department of Atmospheric Sciences, University of Wyoming, for the droplet sampler analysis. Special appreciation is expressed to Dr. A. Miller for providing the micrometeorological data and helpful discussion.

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