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Precipitation from a maritime cloud layer with very low droplet concentrations

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1. Introduction

In very clean air the total concentrations of droplets in maritime stratiform clouds can be very low (Squires, 1958a, b). Interestingly, these clouds sometimes precipitate.

In this note we describe such a case and the meteorological conditions that accompanied it. The measurements were made aboard the University of Washington's Convair C-131A aircraft about 100 km off the Pacific Northwest coastline from about 2000 to 2200 UTC on 2 December 1991. The instrumentation aboard the Convair C131-A for the measurement of aerosol and cloud particles has been described by Hobbs et al. (1991).

The synoptic conditions at 850 hPa (the standard pressure level closest to the cloud layers we studied) are shown in Fig. 1. Air that originated from the sub-tropics was approaching the Washington Coast after being rotated anticyclonically around a surface high-pressure center (10 hPa) located about 1000 km west of northern California. Consequently, the clouds that we sampled formed in an air mass that had a very long trajectory over the Pacific Ocean.

2. Results

Fig. 2 shows the temperatures and dewpoints measured from the aircraft as it climbed from about 30 m above the ocean surface to just above cloud top. Also shown in Fig. 2 is a National Weather Service sounding provided by a rawinsonde released about 3 h later from Quillayute, Washington, which is located northeast of where the aircraft sounding was obtained. The overrunning of cooler marine boundary layer air by the warmer air advected from the sub-tropics is indicated in both soundings by the moist isothermal or inversion layers between 930 and 850 hPa, and by the Quillayute sounding which shows a strong

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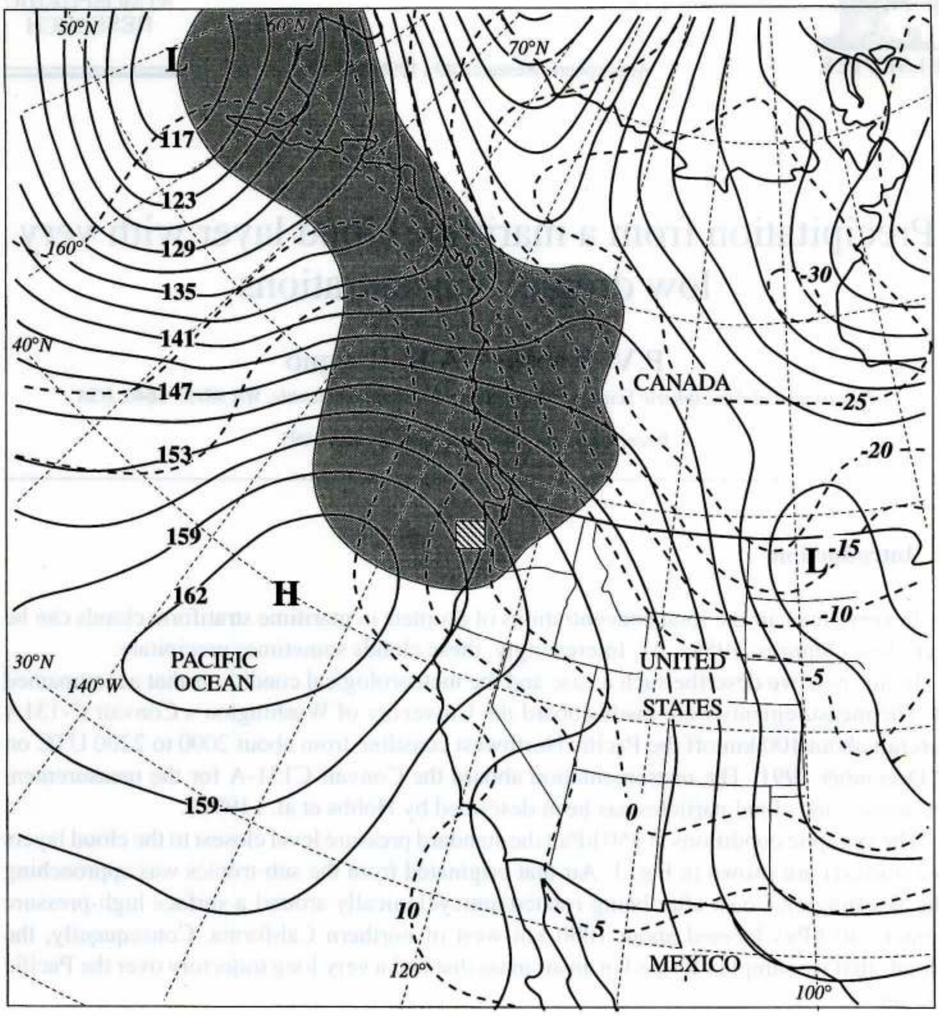

Fig. 1. The 850 hPa constant pressure surface at 0000 UTC 3 December 1991. Solid lines are geopotential height contours (labeled in dm) and dashed lines are isotherms (labeled in °C). The small, hatched square denotes the region where the flight took place. The larger area of shading shows the region of warm-air advection over the northeast Pacific Ocean in which the clouds formed.

capping inversion between 740 and 700 hPa. Another inversion was measured from the aircraft at the top of the marine boundary layer, between 920 and 905 hPa.

Three thin stratocumulus stratiformis cloud layers were encountered in the overrunning air. The upper two layers, which were between 860 and 810 hPa (1.35–1.9 km ASL) and connected in some areas, were sampled extensively. Each layer was about 100–200 m thick. Occasionally the two upper layers merged to form a single layer about 500 m thick. The lowest cloud layer, which was situated near 910 hPa, was only 30–100 m thick and did not interact with the two higher layers. The temperature at the top of the highest cloud layer was 0° to 1°C. The frontispiece shows a photograph of the top of the highest cloud layer; the cloud bow seen in this photograph (produced by the refraction of sunlight in the drizzle-sized drops just below cloud top) was persistent.

We obtained airborne measurements in all three of the stratocumulus cloud layers, starting from the southern coastline of Washington to about 100 km west of Astoria, Oregon (a distance of about 150 km). The top of the highest cloud layer was very smooth and largely featureless, indicating little internal convection or mixing with the dry air above. However, there were occasional isolated smooth, round tops, which gently mounded as much as 30 m above the prevailing tops.

Fig. 3 shows a sequence of cloud microphysical measurements and a schematic of the clouds sampled between 2026 to 2126 UTC. It can be seen from Fig. 3a that the moist layer shown in the sounding profiles of Fig. 2 was not solid cloud but instead consisted of three, often distinct, layers. Fig. 3b shows the presence of occasional modest spikes of liquid water, which indicate some very mild convection from the middle cloud layer into the highest cloud layer. These subdued convective regions contained the highest liquid water

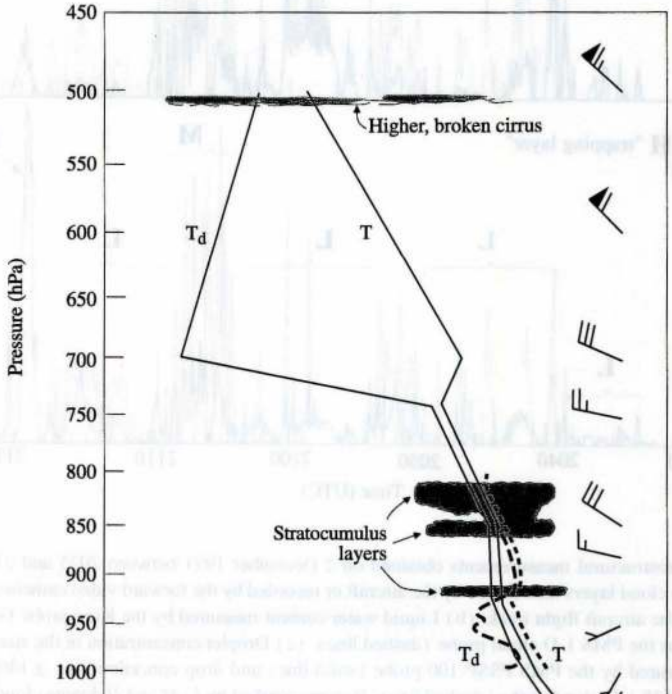

Fig. 2. Temperature and dewpoint soundings from the aircraft between 2025 and 2140 UTC 2 December 1991 (dashed lines), and from the National Weather Service sounding at Quillayute, Washington, at 0000 UTC 3 December 1991 (solid lines). The winds are from the Quillayute sounding. The scalloping shows the locations of the three cloud layers.

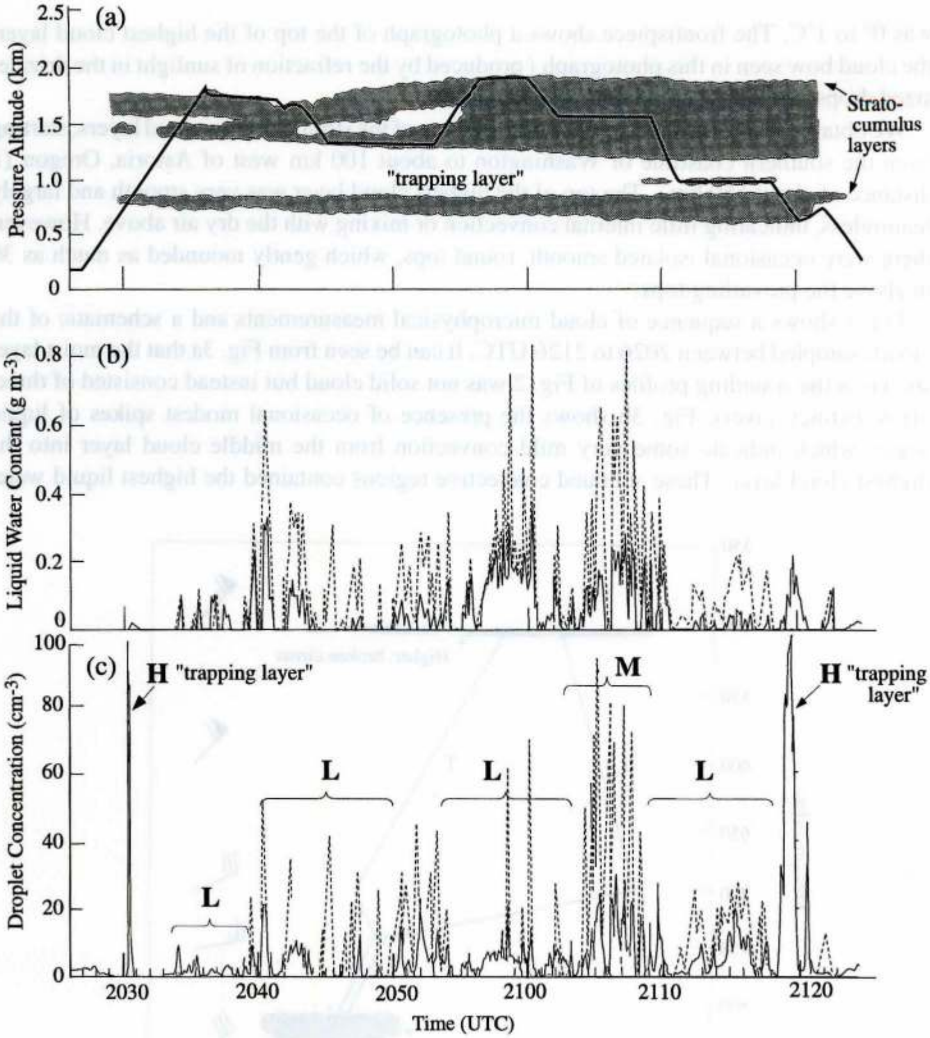

Fig. 3. Cloud microstructural measurements obtained on 2 December 1991 between 2025 and 2125 UTC. (a) Sketch of the three cloud layers intercepted by the aircraft or recorded by the forward video camera on the aircraft. The heavy line is the aircraft flight track. (b) Liquid water content measured by the King probe (solid line) and the King probe plus the PMS 1-D cloud probe (dashed line). (c) Droplet concentration in the size range 3 to 51 μm diameter measured by the PMS FSSP-100 probe (solid line) and drop concentrations ≥ 140 μm diameter measured by the PMS 1-D cloud probe (dashed line). Regions marked by *L*, *M* and *H* denote clouds with droplet concentrations ≤ 10 cm^{-3}, 20–25 cm^{-3} and about 100 cm^{-3}, respectively.

in these clouds. Combined measurements from the PMS 1-D cloud probe (which measures drops from 30 to 310 μm diameter) and the PMS FSSP-100 probe (which measures drops from 2–51 μm diameter) showed liquid water contents briefly reaching 0.8 g m^{-3} on two occasions (Fig. 3b, dashed line). These values are about 90% of the adiabatic liquid water content.

Photograph of the cloud bow observed at cloud top on 2 December 1991.

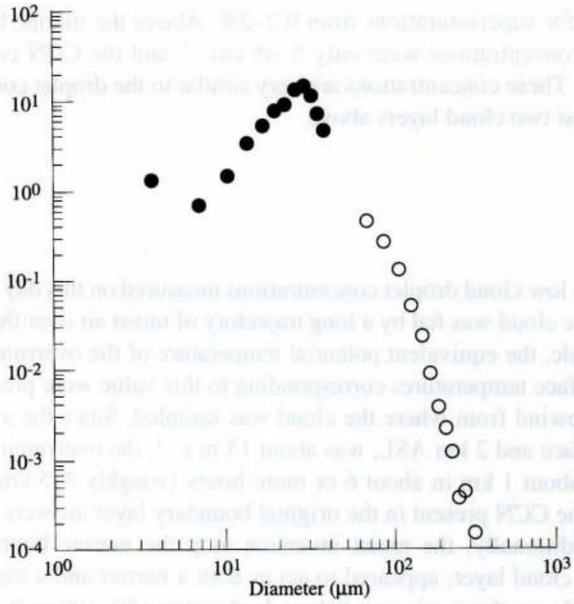

Fig. 4. Cloud drop spectrum measured between 2055 to 2059 UTC near the top of the highest of the three stratiform cloud layers on 2 December 1991. Data are from the FSSP-100 (dots) and from the PMS 1-D cloud probe (circles). PMS FSSP-100 channels in which the concentration was less than 1 cm^{-3}, and the first three channels of the PMS 1-D cloud probe, have been omitted due to the undercounting of particles in these channels.

Droplet concentrations in the subdued convective regions, where the two upper cloud layers merged (Fig. 3c), sometimes attained values of 20–25 cm^{-3} (e.g., regions *M* in Fig. 3c), but generally the droplet concentrations were ≤ 10 cm^{-3} (e.g., regions marked *L* in Fig. 3c). The droplet concentrations in the lowest cloud layer, which was about 50 m thick, were considerably higher (e.g., about 100 cm^{-3}, in regions marked *H* in Fig. 3c). These concentrations are about five times or more greater than those measured in the two cloud layers above, but about the same as those measured in cumulus fractus and stratus fractus clouds in the marine boundary layer just above the ocean surface.

The droplet spectrum within 30 m of the highest cloud top was extremely broad, with drops ≥ 50 μm in diameter present in concentrations of about 500 per liter. Drops as large as 200 μm diameter were present in concentrations as high as 50 per liter. Fig. 4 shows a typical drop spectrum measured during a 5 min period just below cloud tops; the spectrum is quite broad, with the tail extending to drops with diameters of about 300 μm.

Below the base of the middle cloud layer, at about 860 hPa, rainfall rates due to drizzle-sized drops reached 1 mm h^{-1}, and some of the drops were as large as 500 μm. Drizzle also reached the surface, although sporadically. The greatest intensities of drizzle and light rain were measured consistently near 840–860 hPa.

Aerosols were relatively plentiful in the marine boundary layer, which extended from the surface to the first inversion at 910 hPa. However, above this layer aerosol concentrations were extremely low. For example, the marine boundary layer contained Aitken nucleus concentrations of 300–350 cm^{-3}, and cloud condensation nucleus concentrations (CCN) of 15–95 cm^{-3}, for supersaturations from 0.2–2%. Above the marine boundary layer the Aitken nucleus concentrations were only 5–35 cm^{-3}, and the CCN concentrations were only 8–30 cm^{-3}. These concentrations are very similar to the droplet concentrations measured in the highest two cloud layers above.

3. Discussion

The extremely low cloud droplet concentrations measured on this day were probably due to the fact that the cloud was fed by a long trajectory of moist air over the marine boundary layer. For example, the equivalent potential temperature of the overrunning air was about 12°C. Ocean surface temperatures corresponding to this value were present no closer than about 300 km upwind from where the cloud was sampled. Since the average wind speed between the surface and 2 km ASL, was about 15 m s^{-1}, the overrunning layer of air was lifted en masse about 1 km in about 6 or more hours (roughly 4–5 cm s^{-1}). During this period most of the CCN present in the original boundary layer air were probably removed by washout. Additionally, the moist inversion atop the marine boundary layer, which contained a thin cloud layer, appeared to act as both a barrier and a trap for the relatively rich CCN air in the cooler marine air below. In this thin (50–100 m thick) capping cloud layer the cloud droplet concentration was about 100 cm^{-3}, while the air immediately above it was virtually particle free. Finally, since the clouds were stratiform with unusually smooth tops and a very strong capping inversion, there was little vertical overturning within the cloud layers to mix in CCN from above, or to activate new CCN in up currents.

We have encountered, on other occasions, layer clouds with droplet concentrations nearly as low as those described above, and some of these clouds produced precipitation-sized supercooled drops at temperatures as low as −19°C. Therefore, we suspect that clouds with droplet concentrations as low as those described in this paper are not uncommon over the oceans.

Extensive supercooled layer clouds that form in particularly clean maritime air could pose a severe aircraft icing hazard, both within and below the cloud, due to the rapid buildup of ice that can occur in supercooled rain or drizzle (e.g., Stewart et al., 1990; Cober et al., 1995).

Acknowledgements

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