FORMATION OF DROPLETS IN A MARINE STRATOCUMULUS LAYER CONTAINING A SHIP-PLUME

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Abstract. A one-dimensional, adiabatic parcel model was used to calculate cloud droplet spectra from airborne measurements made beneath and within a marine stratocumulus layer that contained ship-produced cloud condensation nuclei (CCN). The calculated droplet mean diameters and concentrations matched the measurements but the width of the droplet spectrum was underestimated. New droplet activation, droplet coalescence and mixing should be included to properly simulate the width of the spectrum. The results of the calculations were consistent with the measurements and satellite imagery which suggests the ship-produced CCN were too small and the ambient CCN were too numerous for the ship-produced CCN to affect the stratocumulus layer. Had fewer ambient CCN existed, the ship-produced CCN likely would have increased droplet concentrations and decreased droplet sizes and generated a "ship-track".

1. INTRODUCTION

Formation of droplets in marine stratocumulus has been successfully investigated using numerical simulation models incorporating explicit microphysics, dynamics and radiation (e.g. Kogan, et al., 1995 and Stevens, et al. 1996). Here, droplet formation is studied using a much simpler adiabatic parcel model to determine how well the model reproduces mean droplet diameters, number concentrations and spectra within a marine stratocumulus layer. Also studied was the effect of ship-produced cloud condensation nuclei (CCN) on the cloud layer.

Fitzgerald (1974) showed that droplet spectra measured near the bases of marine cumulus clouds could be reproduced using a one dimensional, adiabatic parcel model with measured CCN and updrafts. Hindman and Bodowski (1996) showed that mean droplet sizes in marine stratocumulus, estimated from satellite-detected radiances, could be reproduced using a similar model with measured CCN and assumed updrafts. Recently, droplet spectra and CCN measurements have been obtained from a marine stratocumulus layer containing ship-produced particles. These measurements were used here to test how well the parcel model could reproduce the droplet spectra. Further, the results have significance to the detection of ship-modified stratocumulus clouds.

2. MEASUREMENTS

On 21 June 1994, a large, oil-fired naval vessel steamed offshore Monterey, CA underneath a thin, broken stratocumulus layer (Fig. 1a) which topped a well-mixed, buoyancy-driven boundary layer as determined from airborne vertical profiles of sensible and latent heat and buoyancy fluxes (Brooks, Johnson and Rogers, 1995, personal communication). No "ship-track" attributable to the vessel was detected in the 3.7 micrometer radiation reflected from the cloud layer measured by a NOAA satellite (Fig. 1b). Ship-tracks are anomalous linear features most often detected in 3.7 micrometer satellite images of marine stratocumulus layers caused by steaming ships (e.g., Hindman, et al., 1994). The tracks contain more and smaller droplets than the nearby ambient cloud and, thus, cause a brightening in the 3.7 micrometer radiation (Coakley, et al., 1987). Ship-tracks are probably the most dramatic example of inadvertent cloud modification.

Airborne measurements were obtained near the time of the satellite overpass in the region of the cloud layer containing the ship plume (Fig. 2). The cellular nature of the layer is illustrated by the sharp decreases in the liquid water trace (Fig. 2a) corresponding to the light and dark bands in the visible satellite image (Fig. 1a). A distinct and systematic increase in condensation nucleus (CN) concentrations (Fig. 2b) indicated the presence of the

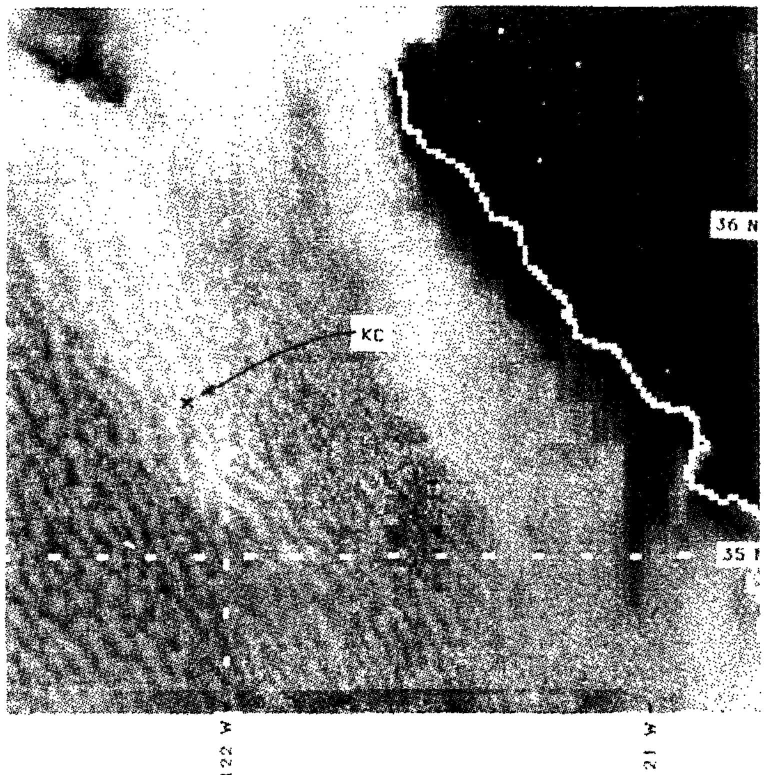

Figure 1a. *A NOAA-9, 0.63 micrometer image showing the USS "Kansas City" position (KC) at 1730 Z (1030 PDT) 21 June 1994 beneath a stratocumulus layer offshore California, USA.*

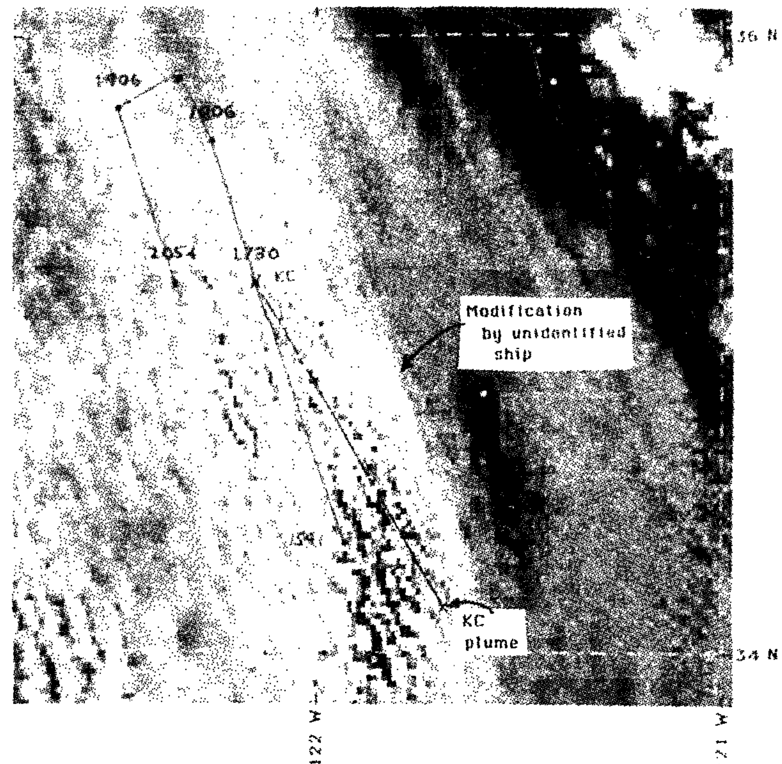

Figure 1b. *The corresponding 3.7 micrometer image shows the "KC" plume did not cause a ship track but a nearby unidentified ship caused a track (images courtesy of Philip Durkee, Naval Postgraduate School).*

ship's plume in the cloud layer. The plume spanned a region of submicron haze droplets (Fig. 2c) and a region of supermicron cloud droplets (Fig. 2d). Thus, the plume was at the edge of a cell in the cloud layer. No increase in droplet concentrations and decreases in droplet sizes (Fig. 2e) were detected in the portion of the plume containing cloud droplets. Further, on the next penetration of the plume, no differences were detected between the region of the cloud layer affected by the plume and the unaffected region in cloud droplet-residue particles from airborne counterflow virtual impactor (CVI) measurements (Fig. 3). Finally, the airborne CCN measurements (Fig. 4) show concentrations in the plume were not greater than concentrations in the nearby ambient air.

These results indicate the CCN produced by the ship were too small and the ambient CCN too numerous to nucleate additional cloud droplets. This conclusion is consistent with inadvertent cloud modification by ship-plumes in regions with few ambient CCN as first identified by Conover (1966) and confirmed by Bowley (1967) and reconfirmed by Hindman, et al. (1994). This conclusion was tested using the adiabatic cloud model.

3. CALCULATIONS

Numerical simulations of cloud droplet formation were performed with the one-dimensional, adiabatic cloud model developed by Nimitz and Plooster (1979). The measured ambient CCN spectra (Fig. 4), subcloud temperature and dew point values and an assumed updraft were used to initialize the model (Hindman and Bodowski (1996) reported model results are not sensitive to values of updrafts in marine stratocumulus). The calculations were terminated when the cloud liquid water content corresponded to the average value measured from the aircraft near the top of the cloud layer. The resulting effective diameter and concentration of the droplet spectrum were close to the airborne measurements in the ambient cloud as illustrated in Figure 5a. This result indicates the model adequately simulated cloud formation in the ambient conditions.

The ambient CCN values, then, were replaced with the values measured in the ship's plume (Fig. 4, ship plume + ambient) and the calculations were repeated. The resulting droplet effective diameter reduced 0.4 micrometers and the concentration increased by 53 per cubic centimeter from the ambient results as shown in Figure 5b, changes within the variations of the measurements.

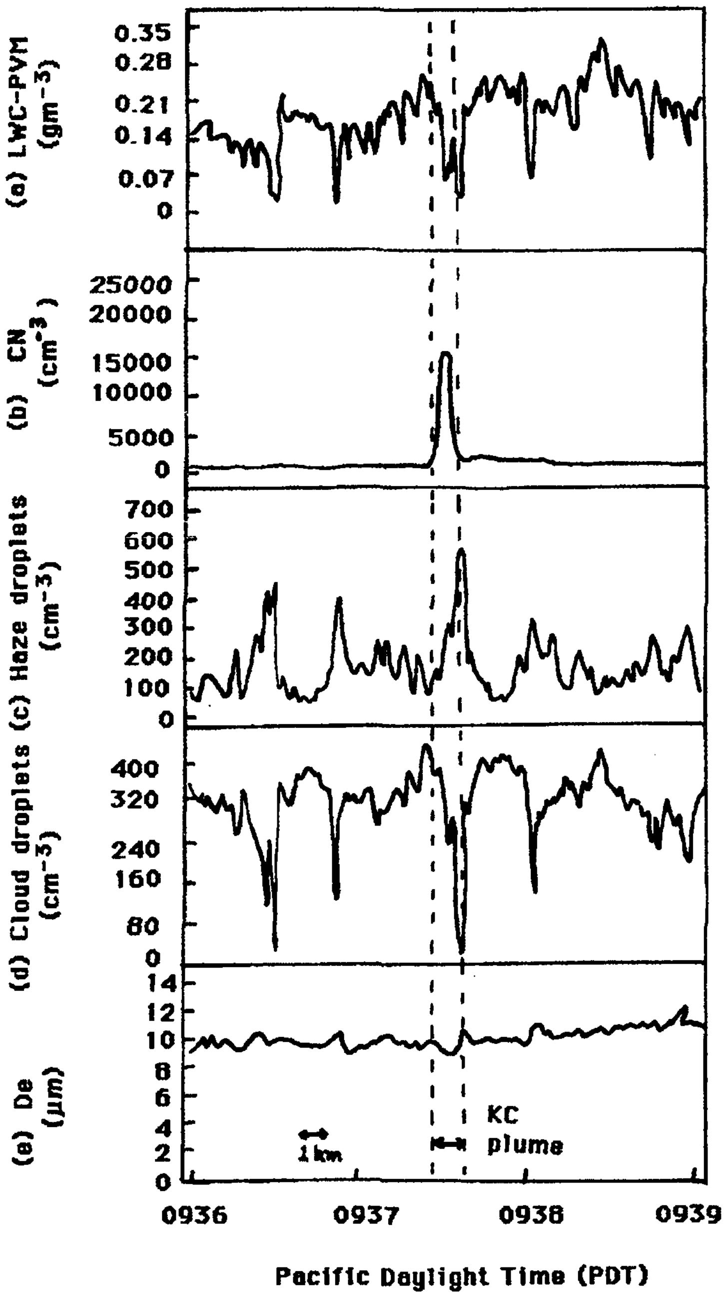

Figure 2. *Measurements from the University of Washington C131 aircraft (Hobbs, 1991) on 21 June 1994 in the "KC" plume which was embedded in the cloud layer 5 miles from the vessel: (a) liquid water content from a PVM (Gerber, et al., 1994), (b) condensation nuclei (TSI Model 3010), (c) haze droplets from a PCASP-100X (Particle Measuring Systems (PMS), Boulder CO), (d) cloud droplets from a FSSP-100 (PMS) and (e) calculated equivalent diameter of the droplet spectra from the FSSP measurements (measurements courtesy of Peter Hobbs, University of Washington).*

Hence, the model calculations confirm that the ship did not produce sufficient CCN with critical supersaturations small enough to nucleate additional numbers of droplets and produce a ship-track in the stratocumulus layer; there were too many of these CCN in the ambient air. In contrast, Hindman and Bodowski (1996) calculated a noticeable modification by ship-produced CCN in a stratocumulus layer that contained few ambient CCN.

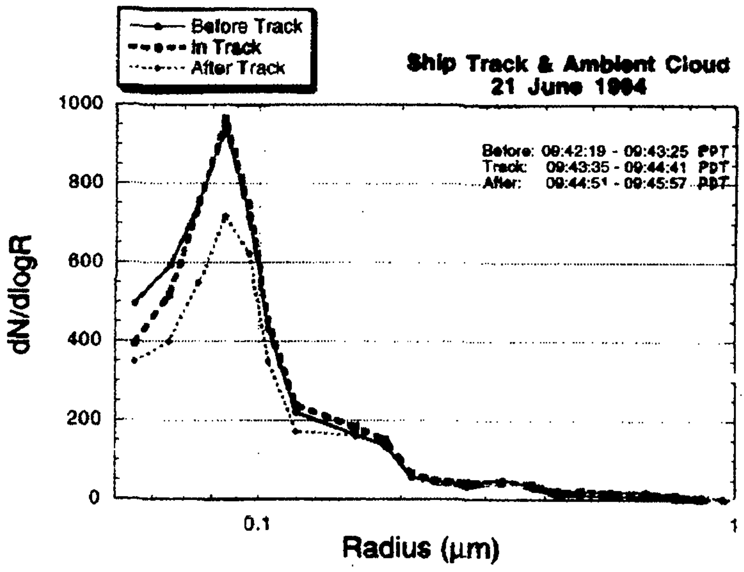

Figure 3. *Measurements from the UW C131 aircraft on 21 June 1994 using a CVI (Noone, et al., 1996). The measurements represent residual particles from droplets which formed in the "KC" plume (measurements courtesy of Kevin Noone, Stockholm University).*

The average droplet spectrum measured near the top of the cloud layer is compared with the calculated spectrum in Figure 6. The spectra agree in mean droplet size and number concentration but the width of the measured spectrum is considerably broader than the calculated spectrum. The model did not include activation of new droplets above cloud base which may account for the absence of the small droplets. Further, coalescence may have been occurring in the cloud because of the large droplets that were not reproduced in the calculations; coalescence was not considered in the model. Recent measurements in marine stratocumulus by Hudson and Svensson (1995) and Hudson and Li (1995) and calculations of drizzle production in marine stratocumulus by Jensen, et al. (1996) and Trautmann (1996) indicate droplet coalescence can occur. Also, spectral broadening may have occurred due to the effects of entrainment and mixing (Young, 1993). Finally, the airborne droplet spectrometer tends to broaden a droplet spectrum (Cerni, 1983) but, not enough to account for the discrepancy. In spite of these limitations, the model reproduced two of three spectra parameters; namely mean droplet size and number concentration.

4. CONCLUSIONS

Cloud droplet formation in a marine stratocumulus layer was investigated using a one dimensional, adiabatic parcel model. The calculations confirmed the observation and

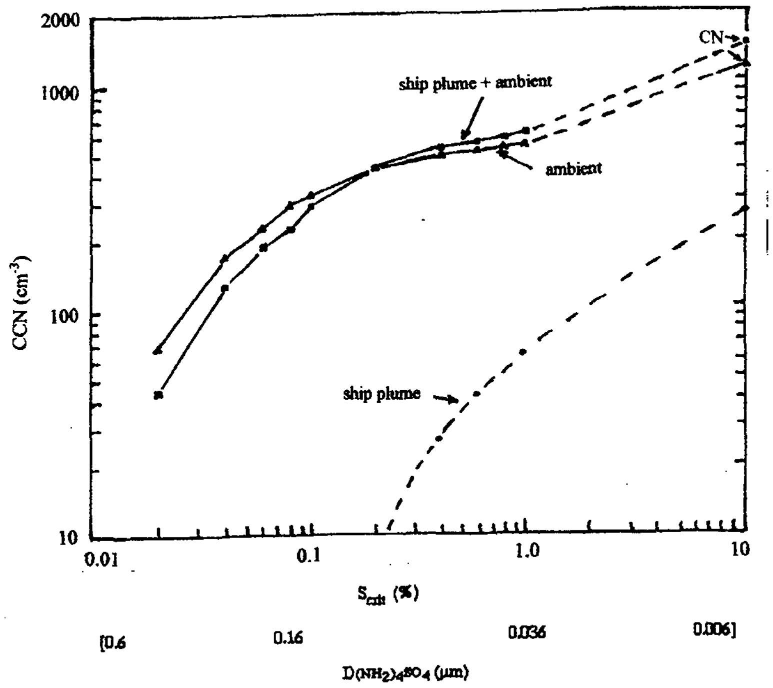

Figure 4. *CCN measurements made from the UW C131 aircraft on 21 June 1994 at 1144 PDT using the chamber of Hudson and Frisbee (1991). The values at 10% are CN concentrations. The measurements were obtained beneath the cloud layer 5 miles from the vessel. The CCN equivalent ammonium sulfate particle diameters are in brackets (measurements courtesy of James Hudson, Desert Research Institute)*

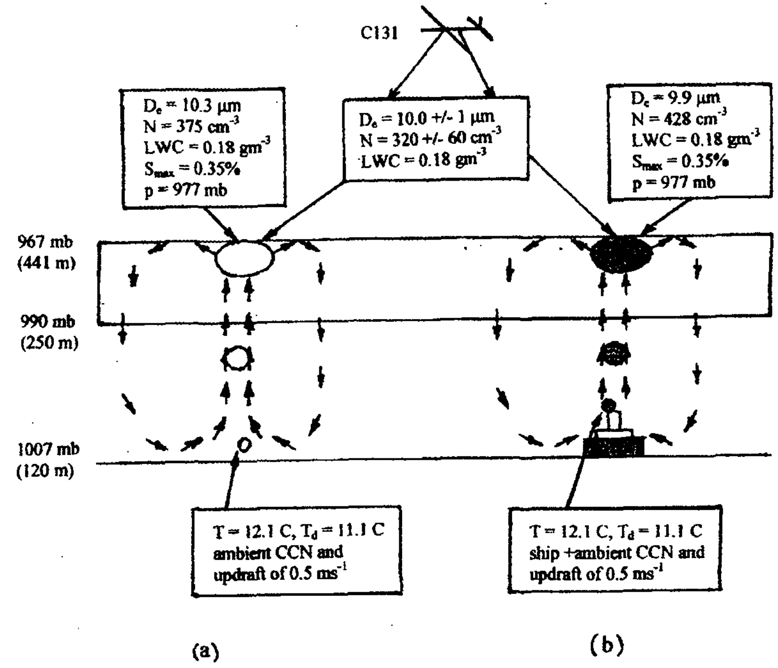

Figure 5. *The calculated droplet sizes and concentrations are consistent with measurements from (a) the ambient cloud and (b) the cloud forming in the "KC" plume. The symbols are as follows: De, droplet effective diameter; N, droplet number concentration; LWC, droplet liquid water content; Smax, cloud maximum supersaturation; p, pressure; T, temperature; Td, dew point.*

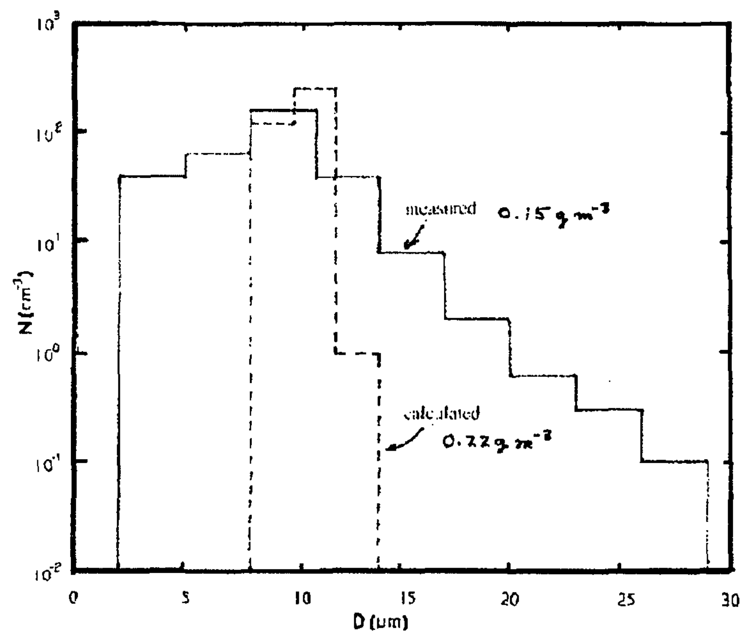

Figure 6. *The solid line is the average cloud droplet spectrum measured during the penetration of the ship's plume indicated in Figure 2 and the dashed line is the calculated spectrum. The cloud liquid water content values from integrating the spectra are indicated.*

measurements that a steaming ship did not produce numerous small droplets in the cloud layer even though its plume reached the layer. This finding indicates the plume contained insufficient CCN with critical supersaturations smaller than the cloud maximum supersaturation because of the numerous ambient CCN. Had fewer ambient CCN been present, the ship-produced CCN likely would have modified the stratocumulus layer producing a ship-track. This is one reason ship-tracks are not a regular occurrence.

The calculated mean diameter and number concentration of the cloud droplet spectrum were close to measured values. This result, when combined with those of Hindman and Bodowski (1996), suggests that the parcel model is adequate to simulate mean droplet diameters and concentrations in marine stratocumulus. However, as shown here, the width of the calculated spectrum was smaller than measured. Activation of new droplets, droplet coalescence and mixing should be included to properly simulate the width of droplet spectra. The model, therefore, is not adequate to simulate the onset of precipitation.

5. ACKNOWLEDGMENTS

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