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PROPERTIES DUE TO CLOUD-AEROSOL INTERACTIONS**

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*Proceedings of 14th International Conference on Clouds and Precipitation  
Bologna, Italy, 18-23 July 2004*

# Evidence for Natural Variability in Marine Stratocumulus Cloud Properties Due to Cloud-Aerosol Interactions

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## 1. INTRODUCTION

Large rifts and gradients are observed frequently in the extensive stratocumulus decks that exist over the eastern areas of the Pacific and the Atlantic. These rifts--areas of low reflectivity and broken cloud conditions--are sometimes large enough to have a large impact on the albedo of the large-scale cloud fields, and indicate substantial natural variability in the properties of the cloud deck (Fig. 1). Consequently, these features present a natural setting to study the relationship between marine aerosol properties and cloud and drizzle characteristics.

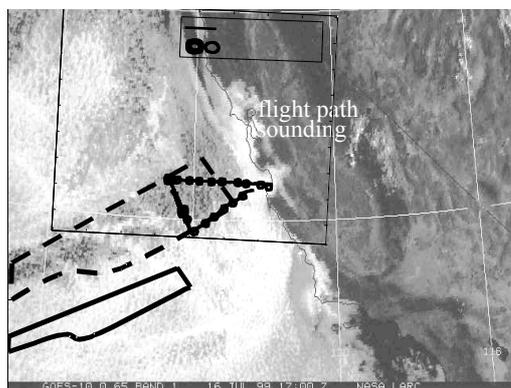


Fig.1 GOES visible Satellite Image of stratus clouds and embedded rift observed off the coast of California, 16 July 1999 1700 UTC, with progression of rift shown by the dashed (1700 UTC) and solid thick line (2300 UTC). Flight path is also overlaid to identify location of soundings (circles) and the path of aircraft.

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Rifts may reflect aspects of the "indirect" aerosol effects where the radiative characteristics and the lifetime of clouds can be modulated by natural and anthropogenic changes in aerosols (e.g. Twomey, 1974 and 1979; Albrecht, 1989; Rotstain, 1999). In rifts, it is hypothesized that CCN concentrations may be reduced relative to those in the surrounding cloud and these lower CCN concentrations may moderate cloud amount due to enhanced precipitation processes (Stevens et al., 2004).

Rifts may also be good indicators of feedbacks between drizzle and observed cloud structure. If CCN concentrations increase, clouds become optically thicker and the probability of precipitation decreases. This situation is consistent with areas of cloud enhancement along ship tracks (shown in Fig. 1) where a smaller mean droplet size is observed (Albrecht, 1989; Durkee et al.).

Hence, once drizzle begins, although the mechanism for initiation is not fully known, CCN are removed and the CCN spectra modified by in-cloud collision and coalescence processes. This cleansing process may lead to an optically less reflective area in the satellite image, or an area in which cloud lifetime decreases due to enhanced drizzle (Albrecht, 1989). If this process is operating, then clean air conditions can support drizzle formation.

## 2. OBSERVATIONS

In this study, aircraft observations from the Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter are used to characterize the variability in drizzle, cloud, and aerosol properties associated with cloud rifts and the surrounding solid clouds observed off the coast of California. A flight made on 16 July 1999 provided measurements directly across an interface between solid and rift cloud conditions (Fig. 1). Aircraft instrumentation allowed for

measurements of aerosol, cloud droplet, and drizzle spectra. CCN concentrations were measured in addition to standard thermodynamic variables and the winds. A Forward Scatter Spectrometer Probe (FSSP) measured size distribution of cloud-sized droplets. A Cloud Imaging Probe (CIP) was used to measure distributions of drizzle-sized droplets. Aerosol distributions were obtained from a Cloud Aerosol Scatterprobe (CAS). The CAS probe measured aerosols, cloud droplets and drizzle-sized drops; for this study. The CAS probe was used to measure aerosols in the size range of  $0.5 \mu\text{m} - 1 \mu\text{m}$ . Smaller aerosols were characterized using an Ultrafine Condensation Particle Counter (CPC) sensor. The CPC was used to measure particles with diameters greater than  $0.003 \mu\text{m}$ . By subtracting different count concentrations measured with the CPC, this probe was capable of identifying ultrafine particles – those falling in the size range of  $3 \text{ nm} - 7 \text{ nm}$  – that are believed to be associated with new particle production.

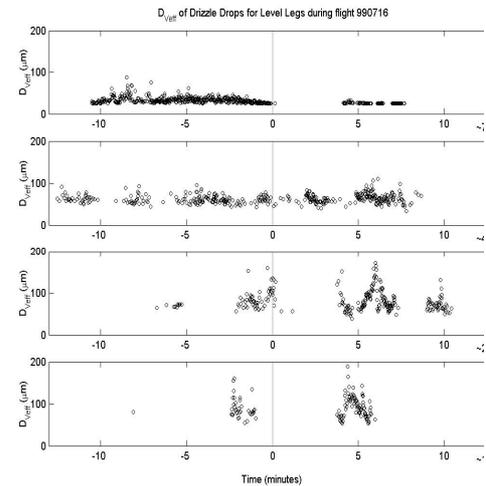
#### 4. RESULTS

The aircraft observations indicate mesoscale patches of clouds and drizzle in the rift area compared with relatively small drizzle production in the solid cloud surrounding the rift. Aircraft soundings were obtained in the rift and the surrounding solid cloud. In addition, constant level legs (20 minutes in duration) were flown at 700, 400, 200, and 100 m across the solid cloud/rift boundary. A relative time scale with a value of 0 at the boundary, positive values in the rift, and negative values in the solid cloud was developed for each of the legs.

Soundings in the rift and the solid cloud areas have very similar thermodynamic characteristics both in and above a strong inversion at about 750 m in both areas. Potential temperature increases about 10 K across the inversion with height and the mixing ratio decreased by about  $2.5 \text{ g/kg}$  over the depth of the inversion ( $\sim 10 \text{ m}$ ).

The variability in the effective diameter ( $D_{\text{eff}}$ ) in the solid and the rift cloud is shown in Fig. 2. Although larger droplets are observed beneath the solid cloud deck adjacent to the rift boundary, the concentrations of these larger droplets is small compared with concentrations observed from the cloud observed in the rift. At 200 meters the effective diameter of drizzle drops in the rift area is greater than that under

the stratus deck. Effective diameters in the rift stratus clouds (400 m level) are slightly less than  $100 \mu\text{m}$ , whereas those associated with the rift peak of about  $180 \mu\text{m}$  at the 200 m level). Although some drizzle is observed beneath the solid cloud near the cloud-rift boundary, the concentrations here are about  $10 \text{ liter}^{-1}$  compared with about  $150 \text{ liter}^{-1}$  in the rift cloud at the same level.



*Fig. 2. Effective diameter for cloud drops along the four horizontal legs. The vertical gray line indicates the boundary between the solid stratus deck and rift region with the solid cloud to the left of this boundary. The x-axis is time of flight in minutes from the rift-cloud boundary*

The variability in drizzle characteristics across the cloud/rift boundary is consistent with a substantial observed variation in CCN concentrations. In the rift area CCN concentrations of  $\sim 30 \text{ cm}^{-3}$  are observed compared with  $\sim 60 \text{ cm}^{-3}$  in the solid cloud. In addition to the CCN variations, there substantial differences in the CN sampled on this flight were observed. Regions of new particle production, as indicated by large concentrations of particles in the  $3\text{-}7 \text{ nm}$  range, are observed consistently near the top of the boundary layer in the clear area adjacent to the edge of the rift (Fig. 5). This area of new particle production is also observed on the leg flown at 700m in the clear area. This region occurs below the inversion and appears to exist in an area influenced by outflow from the solid cloud top. Above the inversion, new particle concentrations in the  $3\text{-}7 \text{ nm}$  range are nearly identical over the rift and the solid cloud areas.

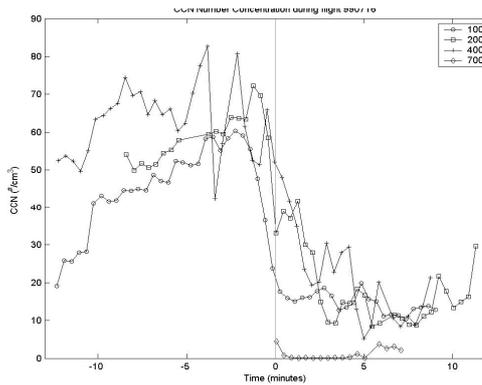


Fig. 3. CCN concentrations for the four level legs. The vertical gray line indicates the border between the solid stratus deck and rift region. In cloud measurements made in clouds have been omitted due to instrument limitations under cloud conditions.

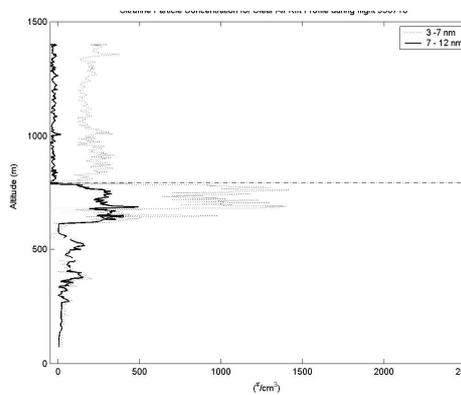


Figure 4. Ultrafine particle profiles obtained in clear area of the that is adjacent to the rift/solid cloud boundary.

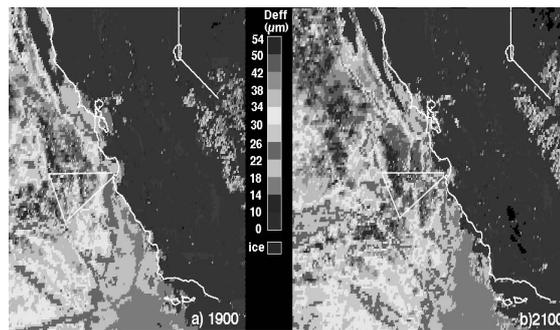


Fig.6. Radiative effective cloud droplet diameter derived from GOES-10 data off the coast of California during 16 July 1999 at (a) 1900 UTC and (b) 2100 UTC.

Although the data are insufficient to document fully the dynamics associated with the stratus deck region and rift areas, microphysics seems to dominate these areas. A large-scale picture of the cloud droplet sizes is available in the satellite analyses. The radiative effective droplet diameter  $D_{eff}$  was derived from the GOES-10 data using the methods of Minnis et al. (1995, 1998) every half hour during the flights. The distribution of  $D_{eff}$  at both 1900 UTC (Fig. 6) and 2100 (UTC) clearly show the rift areas as regions with  $D_{eff}$  values greater than about 35  $\mu\text{m}$ . The solid deck areas around the rifts typically have values of 26 to 35  $\mu\text{m}$ , while those for the clouds farther south away from the rift areas range from 14 to 22  $\mu\text{m}$ . Fig. 6 and similar images for other hours during the day indicate that much of the aircraft-sampled rift was gradually divided into smaller sections apparently as a result of the ship tracks that are evident as nearly linear features of reduced  $D_{eff}$  in Fig. 6 and seen in the visible image (Fig. 1). The introduction of additional aerosols from ships and from the continental air alters the microphysical structure of the rift clouds and

may contribute to a reduction of drizzle and a brightening of clouds in rift areas.

#### 4. DISCUSSION AND CONCLUSIONS

A review of observations from previous stratocumulus studies indicates that observations of drizzle in marine stratocumulus clouds have been generally associated with observations in rift areas. We revisited aircraft observations made during the FIRE stratocumulus experiment in 1986. These observations have been used to examine the microphysical structure for a case where the NCAR Electra (Austin et al., 1995) made an extensive set of observations in a rift while the UK C-130 sampled the surrounding solid clouds. The drizzle and cloud contrasts from these FIRE observations are consistent with our DECS results and provide further evidence for bi-stable cloud conditions where the rift areas are associated with mesoscale drizzle patches and low CCN concentrations compared with lower drizzle rates and higher CCN concentrations in the solid cloud area.

The results in this study provide direct evidence of indirect aerosol effects associated with natural variability in the cloud characteristics. More specifically, these results provide evidence of the second indirect aerosol effect that relates increases in cloud lifetime to decreases in drizzle associated with higher CCN concentrations. This effect is seen in ship tracks observed within the rift during this study that tend to be more reflective in the gradient areas due to a susceptibility for indirect effects in these areas. Decreased albedos and more open cellular structures characterize the rift and gradient areas where drizzle processes work to diminish CCN concentrations. In contrast, ship tracks result from increased reflectivity due to the addition of anthropogenic aerosols into the marine boundary layer. The presence of natural long-lived variations in marine stratocumulus cloud associated with the naturally forming rift areas and man-induced ship tracks clearly supports the theory of bi-stable CCN and cloud states (Baker and Charlson, 1989).

#### 5. ACKNOWLEDGMENTS

This research was supported under NSF Grant ATM 9902416. The efforts of Dr. Phil Durkee in directing the aircraft to the rift area studied during DECS are greatly appreciated. The CCN observations presented were kindly

provided by Tim VanReken. Additionally, we wish to thank Mandy Khaiyer for assistance with analyzing the satellite data. The satellite analyses were supported by NOAA Agreement NA00AABRG0330 under the PACS Program.

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