

## Observations of marine stratocumulus in SE Pacific during the PACS 2003 cruise

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[1] In November 2003, the NOAA Environmental Technology Laboratory (ETL) conducted measurements of Marine Boundary Layer (MBL) stratocumulus clouds, thermodynamic structure, surface fluxes and meteorology in the southeastern Pacific stratocumulus region. The observations were part of a field program to replace the WHOI Ocean Reference Station buoy at 20 S Latitude 85 W Longitude. During the cruise the MBL structure was characterized by a strong capping inversion, periods with well mixed conditions and marine stratus, clear sky periods and periods with moderate vertical gradients of potential temperature and mixing ratio that overlap with periods of small cloud fractional coverage, decoupled layers and low cloud base shallow cumuli clouds. The lifting condensation level (LCL) showed strong variability consistent with the variability of the MBL. Clouds with thickness more than 250 m had drizzle below the cloud base especially during nighttime. Large periods of clear skies were observed at the buoy location, especially just after the solar flux maximum. The aerosol size distribution measurements generally exhibited a bimodal structure. However, abrupt changes in the aerosol size distribution were also recorded, corresponding either with the presence of drizzle (and a depletion of the accumulation mode) or the presence of clear skies (and an increase in the Aitken mode). The stratocumulus observed during the 5-day station at the buoy location revealed a far more complex picture from the one captured during the East Pacific Investigation of Climate (EPIC) cruise to this same location in 2001. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Kollias, P., C. W. Fairall, P. Zuidema, J. Tomlinson, and G. A. Wick (2004), Observations of marine stratocumulus in SE Pacific during the PACS 2003 cruise, *Geophys. Res. Lett.*, 31, L22110, doi:10.1029/2004GL020751.

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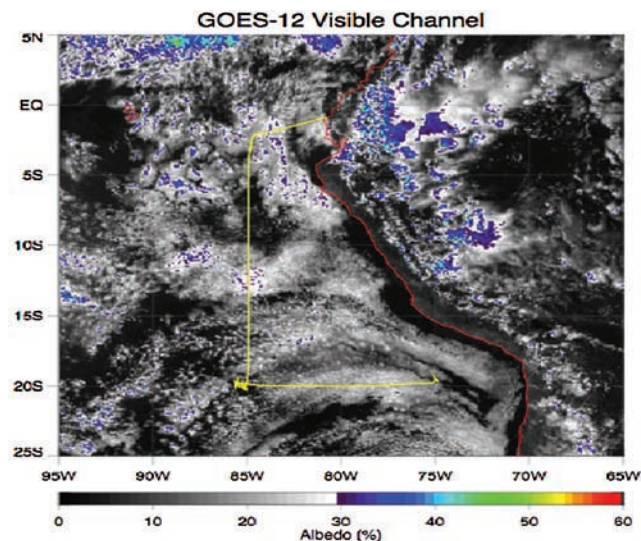
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### 1. Introduction

[2] The southeastern Pacific stratocumulus region reaches close to the Equator, and extends 1500 km offshore all the way south to central Chile (25–30 S) almost year-round [Klein and Hartmann, 1993]. Stratocumulus clouds form over oceans with relatively cold sea surface temperatures (SSTs) and beneath a strong temperature and moisture inversion that caps the MBL [e.g., Albrecht *et al.*, 1988]. Stratus clouds strongly influence global climate because their high albedo (compared with the ocean background) give rise to large deficits in absorbed solar radiative flux at the top of the atmosphere, while their low altitude prevents significant compensation in thermal emission [Randall *et al.*, 1984]. Coupled model studies show that the radiative effects of MBL clouds are essential in producing the observed equatorial cold tongue sea surface temperature structure [e.g., Philander *et al.*, 1996].

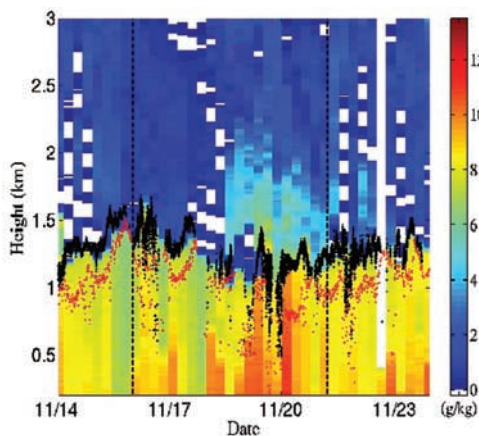
[3] Despite extensive studies in the past [e.g., Albrecht *et al.*, 1988, 1995; Randall *et al.*, 1996] several questions concerning the generation, maintenance and dissipation of marine stratocumulus remain. Such processes include drizzle formation, aerosol influences, entrainment and cloud-top radiative cooling. The presence of clouds in the MBL creates a physical system with radiative, microphysical and dynamical processes [e.g., Albrecht, 1993; Bretherton *et al.*, 2004; Stevens *et al.*, 2003] coupled in a manner that complicates their representation in numerical models [Tiedtke *et al.*, 1989]. Furthermore, the southeastern Pacific stratocumulus region has received relatively little attention in the past (R. A. Weller (Ed.), A scientific plan for EPIC: An eastern Pacific investigation of climate processes in the coupled ocean-atmosphere system, [http://www.atmos.washington.edu/gcg/EPIC/EPIC\\_rev.pdf](http://www.atmos.washington.edu/gcg/EPIC/EPIC_rev.pdf), 1998) and, with the exception of the WHOI buoy, has been scarcely observed with in-situ instrumentation. The stratocumulus regime is important because of its documented feedbacks with ENSO, its large north-south extent encompassing gradients in both microphysical and dynamical conditions and a variety of interesting feedbacks with the S. American continent on many time scales [Li and Philander, 1996].

[4] In this paper observations of marine stratocumulus in the southeastern Pacific during a research cruise as part of the NOAA CLIVAR Pan American Climate Studies (PACS) program are presented. The observations were conducted in November 2003, about a month after the climatological peak of stratus cloud amount [Klein and Hartmann, 1993]. The only significant previous field experiment, the East Pacific Investigation of Climate (EPIC) cruise, was conducted in October [Bretherton *et al.*, 2004]. The sea-going NOAA/ETL remote sensing suite [Fairall *et al.*, 1997]



**Figure 1.** Satellite (GOES-12) visible channel image (November 20, 20:45 UTC) that illustrates the variable cloud conditions encountered during the PACS 2003 cruise. The ship track is shown with the yellow thin line.

includes a 8.6 mm cloud radar (MMCR), a Vaisala CT-25K cloud base ceilometer, and a two-channel (20.6 and 31.6 GHz) microwave radiometer. The ceilometer determines the height of cloud bases with a temporal resolution of 30 sec and vertical resolution of 30 m. The MMCR [Moran *et al.*, 1998] measures the first three moments of the Doppler spectrum, the cloud reflectivity, the mean Doppler velocity and the Doppler spectrum width. The atmospheric column integrated liquid and vapor amounts are retrieved from the microwave radiometer brightness temperatures. Soundings launched every six hours, surface meteorology, turbulence and radiative flux measurements, and aerosol spectrometer measurements provided a near surface complement to the NOAA/ETL remote sensing suite. A unique contribution to the field experiment was two Texas A&M



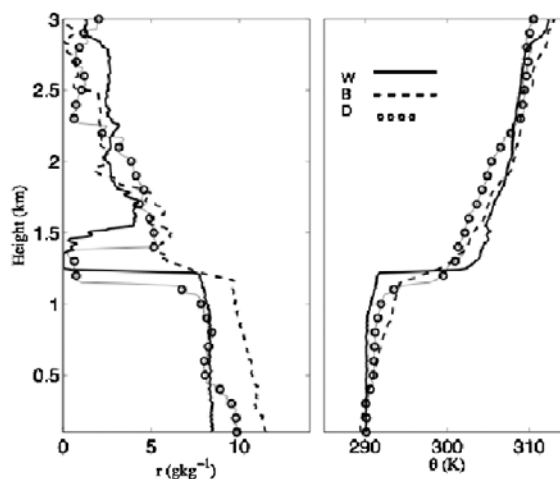
**Figure 2.** Time-height mapping of the mixing ratio  $r$  ( $\text{g kg}^{-1}$ ) from the soundings launched during the cruise. The cloud boundaries are also displayed. The cloud top is retrieved by the MMCR cloud reflectivity (black) and the cloud base (red) by the ceilometer.

instruments, a Differential Mobility Analyzer, and an Aerodynamic Particle Sizer, capable of continually monitoring the aerosol number distribution for particle sizes from 10 nm to 15 micron.

## 2. Vertical Structure of the SE Pacific MBL

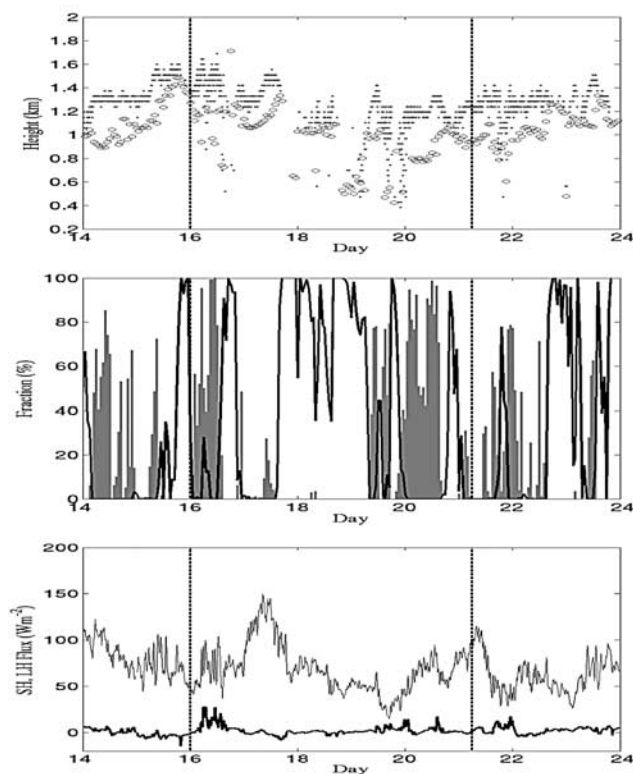
[5] The UNOLS research vessel *Roger Revelle* departed from Manta, Ecuador on November 11. After a short westerly course, the ship continued south to the WHOI buoy at 20° S (Figure 1) and remained at the buoy for 5 days (15–20 November). The cruise concluded with a 3-day easterly route to Arica, Chile. The PACS 2003 cruise track is similar to EPIC 2001 [Bretherton *et al.*, 2004]. During the cruise, variable cloud conditions were observed with extensive periods of complete cloud cover, broken cloud periods and clear sky period, exemplified in Figure 1. The MBL was capped by a strong inversion with typical thickness of 60–150 m, and strong gradients of potential temperature  $\theta \sim 8$ –15 K, and mixing ratio  $r \sim 4$ –7  $\text{g kg}^{-1}$  (see Figure 2). The highest mixing ratio values were observed at the WHOI buoy. The cloud lifting condensation level (LCL) computed from the soundings correlates with the high variability of observed cloud bases and confirms the strong link between the surface and cloud processes. Vertical gradients of the potential temperature and mixing ratio within the MBL were also variable with well mixed periods during persistent stratus cover and decoupled structure during shallow cumuli development into dissipating thin stratus. Figure 3 shows representative soundings observed during three frequently observed cloud types (W-well mixed stratocumulus layer, B-broken cloud layer and D-decoupled conditions with cumuli development at the top of a shallow mixed layer attached on the ocean surface).

[6] Figure 4 shows the stratus cloud boundaries as observed by the vertically pointing active sensors. The ceilometer is immune (in most occasions) to the presence of light drizzle below the cloud base and thus detects the “true” cloud base. The MMCR tends to be more sensitive



**Figure 3.** Representative soundings during three frequently observed cloud types (W-well mixed stratocumulus layer, B-broken cloud layer and D-decouple conditions).





**Figure 4.** Cloud boundaries during the PACS 2003 cruise (top). The cloud top is retrieved by the MMCR cloud reflectivity (dots) and the cloud base (hourly mean, circles) by the ceilometer. Revelle station at the WHOI buoy from November 16 to November 21. The middle panel shows the hourly averaged fraction of clear sky (solid line) radar profiles and drizzle profiles (bar) using a reflectivity threshold of  $-14$  dBZ. The bottom panel shows sensible (thick) and latent (thin) surface fluxes during the same period.

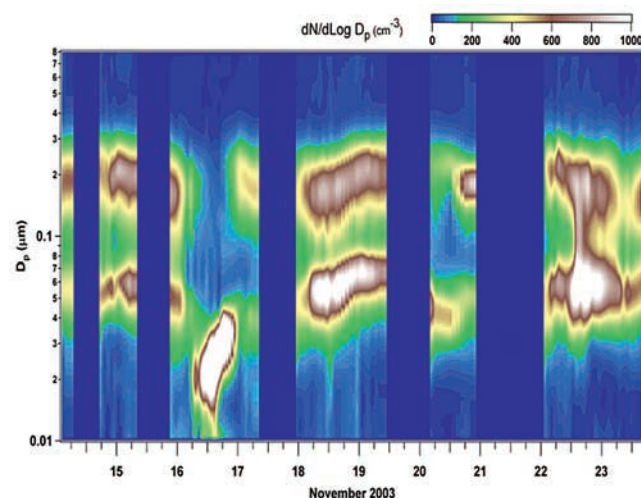
to drizzle than cloud droplets, so drizzle was often observed below the cloud base. The cloud boundary observations cover a 10 days period (2 days moving south toward the WHOI buoy along  $85^{\circ}\text{W}$ , 5 days station at the buoy and 3 days moving east toward Arica along  $20^{\circ}\text{S}$ ). The most variable cloud conditions were encountered at the buoy location. Clear skies were more frequently observed right after local noon and drizzle conditions were more pronounced during nighttime (Figure 4). The fraction of clear skies is defined as the fraction of radar profiles without a cloud detection and the fraction of drizzling conditions is defined as the fraction of radar profiles with maximum reflectivity exceeding  $-14$  dBZ. The mean diurnal pattern in the cloud structure was fairly similar to EPIC 2001 with negligible variations in LCL but substantial diurnal variations for inversion height (1300 m at 0600 UTC to 1100 m at 1500 UTC). Overall, one third of the time (32%) the MMCR detected no clouds, typical cloud tops were around 1200 m and two sets of cloud bases, especially during the buoy station period: a dominant stratocumulus cloud base around 900–1200 m and a lower level cloud base associated with small cumulus clouds with bases around 500 m.

The ceilometer showed clear conditions 20% of the time and a mean cloud base height of 1050 m.

### 3. Surface Fluxes and Aerosol Loading

[7] A near-surface meteorology system [Fairall *et al.*, 1996] deployed during the cruise recorded the SST, and the temperature of the air at 18 m above the sea surface,  $T_{\text{air}}$ . Throughout the cruise the sea-air temperature difference tended to be small ( $\approx 0.5^{\circ}\text{C}$ ), but increased by about  $1^{\circ}\text{C}$  during decoupled periods. During the southward part of the cruise, a decrease of SST from  $23$ – $24^{\circ}\text{C}$  to  $19^{\circ}\text{C}$  was recorded along with an increase in SST to  $21^{\circ}\text{C}$  during the eastward route. The lowest values of SST ( $19^{\circ}\text{C}$ ) were observed in the vicinity of the WHOI buoy. The small difference between SST and  $T_{\text{air}}$ , resulted in small sensible heat fluxes ( $2$ – $15\text{ Wm}^{-2}$ ). As expected over the ocean, the latent heat fluxes were significant ( $\sim 100\text{ Wm}^{-2}$ ) with large variability especially at the buoy location (Figure 4). The higher values of latent heat ( $150\text{ Wm}^{-2}$ ) were observed under solid stratus conditions (November 17) and the lowest ( $50\text{ Wm}^{-2}$  on November 19) during broken cloudy conditions with low LCL (500–600 m), cumulus, decoupled MBL sounding conditions and large cloud free areas in the vicinity of the buoy station. The downward broadband long wave radiation was around  $380$ – $400\text{ Wm}^{-2}$  under cloudy conditions. The local solar maximum often coincides with periods of clear skies and thus the magnitude of the shortwave forcing by MBL clouds was greatly reduced.

[8] Observations of the aerosol size distribution by the Texas A&M instruments during the cruise are shown in Figure 5. A bimodal distribution is clearly visible throughout the sampling except for a couple of unique events. Double-peaked aerosol size distributions have been observed before in remote ocean locations away from land influence [e.g., Hoppel *et al.*, 1990]. The cycling of aerosols through non-precipitating clouds causes a minimum in the aerosol size distribution between the Aitken and CCN portion of the size distribution. The small size mode (Aitken



**Figure 5.** Aerosol particle number as a function of diameter (10-nm up to 15- $\mu\text{m}$ ) from a Differential Mobility Analyzer, and an Aerodynamic Particle Sizer, deployed by Texas A&M during the PACS 2003 cruise.

mode, non-CCN aerosols) is centered on 0.05- $\mu\text{m}$  where the large size mode (accumulation mode, CCN aerosols), is centered on 0.2- $\mu\text{m}$ . The bimodal aerosol size distribution was temporally interrupted twice. The first event occurred on the late hours of November 15 and continues into the 16. Initially, a sharp decrease of the total concentration of the accumulation mode aerosols (from 200  $\text{cm}^{-3}$  on November 15 22:00 UTC to 50  $\text{cm}^{-3}$  on November 16 02:00 UTC) is observed. The sharp decrease in the total concentration of accumulation mode (0.1–0.3  $\mu\text{m}$ ) aerosol particles is accompanied by heavy drizzle periods (Figure 4) and a further decrease of the total concentration to 20  $\text{cm}^{-3}$  by 12:00 UTC. Finally, a gradual restoration (150  $\text{cm}^{-3}$ ) of the accumulation mode by 24:00 UTC is observed under clear skies conditions and development of a stratus layer by the end of the day (November 16). The second event occurred during the 22nd and it is characterized by an increase of the total aerosols concentration to 800  $\text{cm}^{-3}$  (highest observed) and the separation between the two modes was not as pronounced. The total concentration of accumulation mode aerosols increased from 100 to 300  $\text{cm}^{-3}$  within 12 hours (02:00 to 14:00 UTC, November 22). Marine stratus with evidence of sporadic light drizzle events was observed early on, while extensive clear skies (Figure 4) developed during and after the maximum in the total aerosol concentration (14:00 UTC). The drizzling conditions during the November 22 event were less intense than the November 16 event.

#### 4. Discussion

[9] The PACS 2003 cruise ([www.etl.noaa.gov/programs/pacs/stratus03](http://www.etl.noaa.gov/programs/pacs/stratus03)) provided an unprecedented data set of subtropical marine stratocumulus clouds over the southeastern Pacific. During the cruise, the MBL structure was characterized by the strong capping inversion and often well mixed vertical structure. However, moderate vertical gradients of potential temperature and mixing ratio were observed particularly at the WHOI buoy location. The vertical structure of the MBL was reflected in the cloud structure with periods of overcast marine stratocumulus interchange with clear skies periods (20%), and periods of small cloud fractional coverage and decoupled layers with low cloud base shallow cumuli clouds. The LCL derived by the soundings had strong variability consistent with the variability of the MBL. Periods of clear skies were observed at the buoy location, especially just after the solar flux maximum. Drizzling conditions were more frequently encountered during nighttime and their cooling and moistening effect on the MBL was documented by the soundings. Stratus clouds with cloud thickness more than 250 m had drizzle below the cloud base. The aerosol size distribution was bimodal (Aitken and accumulation modes), however two interesting events with abrupt changes in the sizes and number concentration were recorded, one associated with the presence of drizzle and the other with clear skies.

[10] The stratus observed at the buoy location during this cruise revealed a different picture from the one captured during the EPIC research cruise conducted on October 2001. During EPIC 2001, the MBL was well mixed throughout

the cruise (similar track and 6 day station at the WHOI buoy) resulting in small LCL variability, strong capping inversion, with episodes of higher relative humidity subsiding from aloft into the boundary layer and periods of higher humidity during drizzling periods. Strong diurnal cycles in the inversion height, cloud thickness, cloud top height and liquid water path of marine stratocumulus were documented at the buoy location during EPIC 2001 but nearly no clear skies were reported, despite the presence of persistent and strong drizzling conditions. This reflects the complexity of the coupled atmospheric-ocean system and underlines the need for future systematic observations of stratus clouds in the region.

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