4.4 BOUNDARY LAYER, CLOUD, AND DRIZZLE VARIABILITY IN THE SOUTHEAST PACIFIC STRATOCUMULUS REGIME

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1. INTRODUCTION

During the last two decades, marine stratocumulus clouds have been the focus of theoretical/modeling studies (e.g. Bretherton and Wyant 1997) and field experiments (e.g. Albrecht et al. 1988; 1995; Stevens et al. 2003; Bretherton et al. 2004). Stratocumulus clouds affect Earth's radiation budget primarily by reflecting shortwave radiation back to space (Randall et al. 1984). Thus, accurate representation of marine stratus in Global Climate Models (GCMs) is needed for realistic simulations of Earth's climate. However, this requires a better understanding of their radiative, microphysical and dynamical properties, and the thermodynamic structure of the Marine Atmospheric Boundary Layer (MABL). In addition, the climatological variability of marine stratocumulus decks at their respective areas (e.g. Klein and Hartmann 1993; Stevens et al. 2003) is required. One of the most prevalent stratocumulus cloud decks in the world is located over the subtropical South-East (SE) Pacific, extending about 1500 km offshore from the Equator to the latitude of central Chile (25-30°S) (Klein and Hartmann 1993). In addition to the large latitudinal extent, the interaction with El Nino-Southern Oscillation (ENSO) and the special morphology of the western South American continent also contribute to the unique character and high importance of the SE Pacific stratocumulus regime (Li and Philander 1996).

In this study, observations from mm-wavelength radars, wind profilers, ceilometers, soundings and surface meteorological data collected during three research cruises are used to explore the variability of the MABL, clouds and drizzle in the SE Pacific. A short description of the routes followed by the research vessels each year and the instrumentation onboard is presented in the following section. The analysis presents cruise-composite thermodynamic and cloud structures, cloud boundaries, inversion strength and height, and vertical mixing.

2. BACKGROUND, CRUISES DESCRIPTION AND INSTRUMENTATION

An important element of the Eastern Pacific Investigation of climate (EPIC) long-term monitoring is the Stratus Ocean Reference Station (Stratus ORS) that was deployed in October 2000 at the geographical location of 20°S, 85°W by the Woods Hole Oceanographic Institution (WHOI) Upper Ocean Processes (UOP) group. The recovery and replacement of the Stratus ORS buoy was one of the primary objectives of the EPIC 2001 stratocumulus cruise (hereafter called EPIC 2001) (Bretherton et al. 2004). Thereafter (with an exception of 2002), regularly-scheduled buoy maintenance and replacement cruises provide scientists with an opportunity to deploy remote sensors and other instrumentation in these remote oceanic areas for the study of the SE Pacific stratus deck. The Stratus 2003 (Kollias et al. 2004) and Stratus 2004 research cruises (part of the PACS/EPIC enhanced monitoring and process studies implementation schedule) provide along with EPIC 2001 a unique data set for the study of the variability of stratocumulus clouds and MABL in the subtropical SE Pacific. In addition, these measurements allow comparison studies of the SE Pacific stratocumulus with the better-studied stratocumulus of the NE Pacific, and to those sampled in a less instrumented Chilean cruise off of central Chile in October 1999 (Garreaud et al. 2001).

The ship track during each of the three cruises under consideration is shown in Fig. 1. During EPIC 2001 and Stratus 2003, the research vessels followed similar – but not identical – paths, while the Stratus 2004 cruise had a different, more southward route. The EPIC 2001 cruise started from the Galapagos Islands, where the NOAA

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research vessel *Ronald H. Brown* (hereafter called the *Brown*) was stationed for a few days following the first leg of the field campaign. From this point, the *Brown* steamed west on October 9th to 95°W and then south along the remainder of the TAO buoy line into the SE Pacific stratocumulus-capped boundary layer. After stopping for approximately 6 days (October 16-22) at the location of the Stratus ORS buoy, the *Brown* reached the port of Arica in northern Chile, on October 25th. During Stratus 2003, the UNOLS research vessel *Roger Revelle* (hereafter called the *Revelle*) departed from Manta, Ecuador on November 11th. After a short southwesterly course, the ship continued south to reach the WHOI buoy, where it remained for about 5 days (November 15-20). The cruise concluded with a 3-day easterly route to Arica, following a route similar to the EPIC 2001 cruise. Arica was the starting point of Stratus 2004. The *Brown* headed west along the 20°S line, until it reached the Stratus ORS location, where it remained stationed for 5 days as well (December 11-16). After a short westerly route until 90°W, the ship followed a southeasterly route into the southernmost part of the stratocumulus regime and concluded the trip in Valparaiso, Chile on December 24th, with a short southerly transect along the coast of central Chile.

Although the cruise paths followed by the *Brown* in 2001 and 2004 and the *Revelle* in 2003 are quite different in general, there is sufficient overlap in domains for comparisons between the three field experiments. All the cruises included a station at the Stratus ORS, for 5 to 6 days each time. In this study, we focus on the buoy location and take advantage of the unique 3-cruise dataset, to study and compare the diurnal evolution of the cloud-topped boundary layer and attempt to extract the statistical characteristics of the marine stratus deck. The transect along 20°S from 75° to 85°W (hereafter the 20°S transect) is also common with all three research cruises, and could be ideal for studying the evolution of the MABL in the transition from the pure marine environment with low aerosol concentration to the coastal polluted environment with higher aerosol loading. The temporal lag of the three cruises (October 2001 – November 2003 – December 2004) will allows us to extract a monthly variability regarding the afore-mentioned properties, and seek signs of interannual variability, always under the context of the influence of large-scale dynamics.

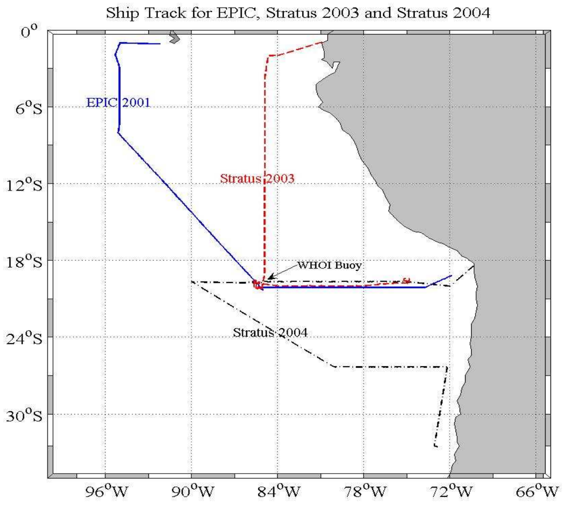

Fig. 1. The routes that the *Brown* and the *Revelle* followed during EPIC 2001, Stratus 2003 and Stratus 2004.

The EPIC 2001, Stratus 2003 and Stratus 2004 research cruises were collaborative efforts among various institutions and universities. An extensive suite of instruments was deployed onboard the research vessels for making measurements of boundary layer clouds, thermodynamic structure, surface fluxes and near-surface meteorology. The remote sensors that were used in each cruise and their respective products are briefly described in Table 1. All cruises included a ceilometer, a microwave radiometer and an 8.6-mm Doppler cloud radar (although the later suffered a component failure early in the Stratus 2004 cruise), as part of the NOAA Environmental Technology Laboratory (ETL) Portable Cloud Observatory (NPCO). A complete air-sea interaction flux system (Fairall et al. 1997) provided surface meteorology, turbulence and radiative flux measurements. Regularly launched rawinsondes during the three field experiments provided high resolution vertical profiles of the MABL thermodynamic structure. During EPIC 2001 the frequency of the sounding launches was relatively high (8 per day), compared with that in Stratus 2003 (4 per day) and Stratus 2004 (4 per day with the exception of 6 per day while at the ORS location). The 2001 and 2004 cruises also included the operation of the C-Band Radar onboard the *Brown* and a 915-MHz wind profiler, while a high resolution but low sensitivity 3.2-mm Doppler cloud radar was only used during Stratus 2004.

Table 1. A list of the remote sensors onboard the *Brown* and the *Revelle* and the respective products.

Remote Sensor	Cruise	Technical Specs	Product
FMCW* radar	Stratus 2004	94-GHz (3.2mm), vertically pointing	Reflectivity, Doppler Velocity & Spectrum Width
MMCR** pulse radar	All three	35-GHz (8.6mm), vertically pointing	Reflectivity, Doppler Velocity & Spectrum Width
Brown C-Band radar	EPIC, Stratus 2004	5.6-GHz (5.4 cm), scanning	Reflectivity, Radial velocity
Wind Profiler	EPIC, Stratus 2004	915-MHz (32.8 cm)	Time-height profile of wind speed/ direction
Ceilometer	All three	Lidar (Vaisala CT-25K)	Time-height profile of cloud base
Microwave Radiometer	All three	3-channels: 20.6, 31.6, 90GHz	Column integrated liquid and vapor amounts
* Frequency Modulated Continuous Wave ** Millimeter Cloud Radar			

3. PRELIMINARY RESULTS ON THE MABL VERTICAL STRUCTURE

During all three cruises, a wide range of cloud conditions were encountered that included extensive periods of complete cloud cover, broken-cloud and clear-sky periods. A closer look at the data reveals qualitative differences in the MABL structure and cloud conditions from year to year. Well-mixed stratocumulus-capped boundary layer conditions were observed throughout the EPIC 2001 cruise (Bretherton et al. 2004). The 90% cruised-averaged cloud fraction from the ceilometer confirmed the presence of few broken-cloud and nearly no clear-sky periods. The observed MABL cloud cover during the Stratus 2003 cruise was different (Kollias et al. 2004). The MABL structure was characterized by the strong capping inversion and often well mixed vertical thermodynamic structure similar to these observed during EPIC, but there were also days – especially at the ORS location – with moderate vertical gradients of potential temperature and mixing ratio. This was reflected in the cruise-averaged cloud fraction derived by the ceilometer measurements (about 80%). The rare presence of decoupled layers with shallow cumuli clouds was also a MABL feature not observed during EPIC 2001. The general features observed in Stratus 2003 were also documented during Stratus 2004.

Preliminary analysis of the data collected during the third cruise in the subtropical SE Pacific stratocumulus regime reveals additional differences and features with respect to the previous field experiments. The boundary layer was relatively well-mixed in the beginning of the cruise (westerly route towards the ORS location), with rather thin clouds and a good correspondence between LCL and cloud base. The MABL conditions changed while the ship was stationed at the buoy location; the boundary layer became deeper and strong vertical gradients of temperature and moisture were observed. These conditions persisted throughout the southeasterly course towards the South American coast with persistent decoupled MABL conditions for several days. During the same period, the cloud deck was characterized by relatively high and thin stratocumulus clouds and the occasional formation of lower cloud-base cumuli clouds that rise into the stratocumulus layer.

The MABL mixing ratio time-height evolution, as revealed by the rawinsondes launched during the three cruises, is shown in Fig. 2. The cloud boundaries and the lifting condensation level (LCL) are also displayed. The three panels of Fig. 2 demonstrate the differences between the boundary layer and cloud structures captured during the three observational time periods and illuminate the complexity and variability of the SE Pacific stratocumulus regime. A future goal of this study is to relate the observed cloud variability to the large-scale dynamics and boundary-layer processes, and to address the issue of whether the variability is mostly driven by large-scale dynamics and atmospheric (or even oceanic) circulation or it is entirely due to internal MABL dynamics (Rozendaal and Rossow 2003).

Another interesting feature observed during Stratus 2004 was the elevation (height increase) of the sharp inversion that capped the MABL while the *Brown* remained stationed. The inversion height was about 1.2 km at the beginning of the 2004 buoy period (same levels as EPIC 2001 and somewhat lower than Stratus 2003), and gradual increased to 1.7 km three days later. Once the Brown departed from the WORS station and headed southeast, the height of the inversion increased even more, extending to 1.8-1.9 km, before decreasing to a minimum (~500 m) near the coast (lower panel of Fig. 2). Such boundary layer depths were not encountered during the EPIC 2001 and Stratus 2003 cruises; the maximum inversion heights observed then did not exceed 1.5 km. During the 2001 and 2003 buoy periods, the boundary layer actually became somewhat shallower with the course of time. From 1.4-1.5 km upon the arrival at the ORS station in 2003, the boundary layer depth decreased gradually to about 1.1 km three days later, deepened again during the following day by about 200 m and remained approximately constant at 1.3 km until the end of the cruise, including the final easterly route to Arica (Fig. 2 – middle panel).

The upper panel of Fig. 2 indicates a strong diurnal cycle of inversion height (Bretherton et al. 2004). Similar diurnal variability in the inversion height can be seen at the moisture structure observed in 2003 and 2004 (middle and lower panels of Fig. 2), although the cycle is weaker and less regular. This can be partially attributed to the reduced frequency of rawinsondes launches during 2003 and 2004. The cloud base height does show a strong diurnal variability during Stratus 2004, in contrast to the EPIC observations that showed almost no cloud base diurnal variability. Bretherton et al. (2004) point out, however, that they were expecting most of the cloud thickness variations during EPIC to come from a varying cloud base rather than inversion height variations. Finally, the gaps observed in the ceilometer cloud base measurements during Stratus 2004 (especially after December 13th) are due to the malfunctioning of the ceilometer during the daytime, and are not necessarily associated with the non-existence of clouds.

Nevertheless, the ceilometer malfunction did not affect the observation of the cloud base height increase during the boundary layer deepening observed after December 13th. This cloud base height increase is highly correlated with the presence of strong vertical gradients of the boundary layer moisture and significant divergence between LCL and cloud-base height, indicating that the subcloud layer remained "decoupled" for several days. Decoupled conditions are first observed during the third day that the *Brown* is stationed at the buoy location and persist during the southeasterly route that the Brown followed afterwards. The decoupled MABL conditions resulted in decrease of the cloud thickness and the intermittent presence of shallow cumuli clouds below the high stratocumulus cloud base. Lower cloud bases are indicated by the ceilometer cloud base estimates (black dots near 600-800 m in the lower panel of Fig. 2). The daily ceilometer backscatter intensity and cloud base height were compared with FMCW reflectivity data (graphs not shown here), revealing that some of the low-level cloud-base returns correspond to drizzle, while the rest are associated with low cumulus clouds.

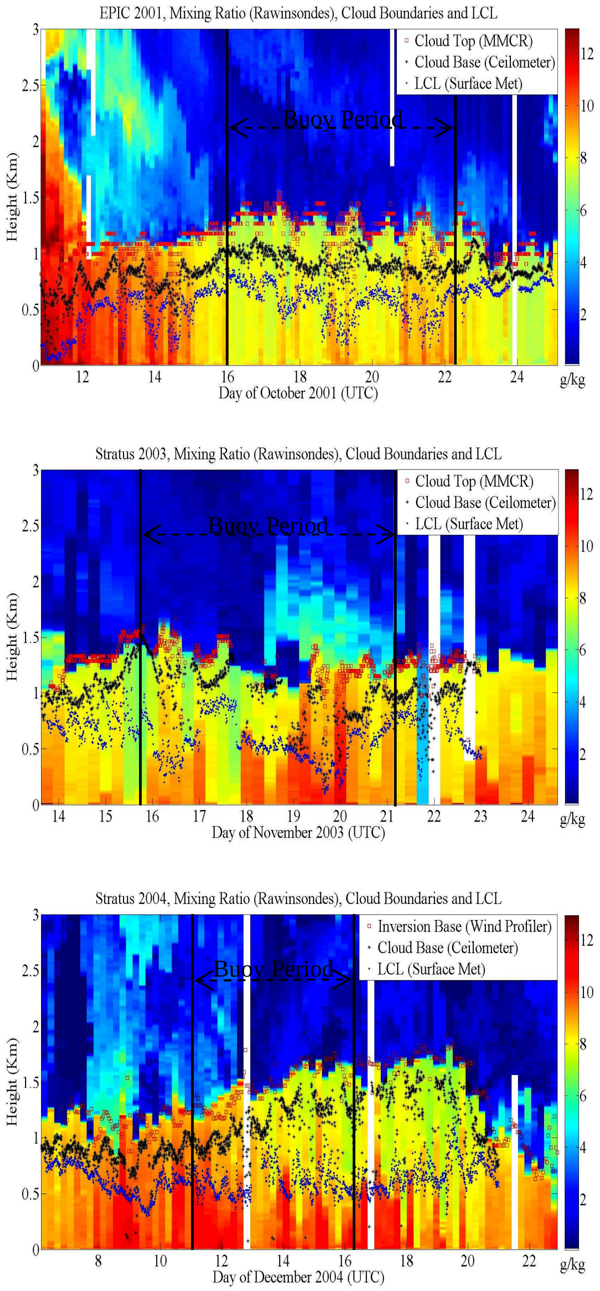

Fig. 2. Time-height mapping of mixing ratio r (g/kg) from the soundings launched during EPIC 2001 (upper panel), Stratus 2003 (middle panel) and Stratus 2004 (lower panel). The cloud boundaries and the LCL are also displayed. The cloud top (red) is retrieved from the MMCR for EPIC and Stratus 2003, while for Stratus 2004, it is approximated by the inversion base height, derived from the wind-profiler reflectivity. The cloud base (black) is derived from the ceilometer and the LCL (blue) from surface met data. All estimates are 10-min averaged or linearly interpolated from a higher resolution, with the exception of the hourly averaged inversion base height. The periods when the vessels were stationed at the WHOI buoy (20°S, 85°W) are bounded by black vertical lines, while white segments indicate missing or bad sounding values.

Besides the buoy location, all cruises sampled the transect along the 20°S parallel from the ORS location (85°W) to Arica, Chile (~70°W). During Stratus 2004, the 20°S transect was sampled in the opposite direction, since Arica was then the departure and not the ending point of the cruise. During the EPIC 20°S transect, the inversion height dropped to the lowest value of the entire period of observations (~850 m at 80°W), and then slightly increased again and remained around 1 km for the remaining two days of the cruise. During this period, the boundary layer was well-mixed and the LCL and cloud base were well correlated. The respective transect in Stratus 2003 was characterized by a constant inversion base height of approximately 1.3 km, as we mentioned earlier, and variable vertical gradients of temperature and moisture. The mixing ratio values observed during the Stratus 2003 20°S transect were higher (~ 8-10 g/kg) than the EPIC 2001 period (~ 6-8 g/kg). During the 2004 transect, the boundary layer was well-mixed with high mixing ratio values (~ 9-12 g/kg). After a gradual decrease during the first two days of the cruise, the inversion base rises again to reach 1.2 km at the beginning of the buoy period.

4. CONCLUSIONS

The analysis of the MABL and cloud variability during the three cruises in the SE Pacific illustrates the complexity of the MABL and the rapid change of the cloud conditions. Well-mixed conditions were observed during the EPIC field experiment, with strong diurnal cycle, persistent drizzle events during the nighttime and coupled conditions despite the heavy drizzling rates. The 2003 and 2004 cruises revealed a different and more complex picture with respect to the EPIC findings, especially for boundary layer structure and evolution, even for the same spatial domains (WHOI buoy location) and for adjacent months (October-November-December). This highlights the need for more in-situ observations and enhanced monitoring of the SE Pacific MABL.

ACKNOWLEDGEMENTS

This research was sponsored by NOAA Research Grant NA17RJ1226.

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