2R.2 PROPERTIES OF SE PACIFIC STRATOCUMULUS USING MM-WAVE RADARS AND OTHER REMOTE SENSORS

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1. INTRODUCTION

During the last two decades, marine stratocumulus clouds have been the center-piece of many theoretical/modeling studies (e.g. Bretherton and Wyant 1997) and field experiments (e.g. Albrecht et al. 1988; Albrecht et al. 1995). This type of clouds is mainly observed at low levels over the eastern side of the subtropical oceans, where the conditions (cool surface waters – warm, dry air subsiding aloft) favor the creation of a sharp temperature and moisture inversion that caps the Marine Atmospheric Boundary Layer (MABL) and leads to the trapping of the clouds at its top (Klein and Hartmann 1993). Both surface-based cloud climatologies (Klein and Hartmann 1993) and satellite studies (Ramanathan et al. 1989) have clearly indicated the impact of boundary layer clouds on the global radiation budget; their high albedo results in a substantial decrease of the amount of solar radiation reaching the ocean's surface, while their low altitude corresponds to a small air-sea temperature difference and thus, allows for little change in thermal radiation emitted to space. Although the role of stratocumulus clouds in affecting the radiation balance by cooling the ocean was recognized through early studies (e.g. Randall et al. 1984), the growing need of a more accurate representation in the Global Climate Models (GCMs) has engaged many scientists in the pursuit of a better understanding of their radiative, microphysical and dynamical properties, the thermodynamic structure of the MABL as well as the climatological variability of the respective areas (e.g. Stevens et al. 2003).

One of the most prevalent stratocumulus cloud decks in the world is located over the subtropical southeast 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 (e.g. the presence of Andes) also contribute to the unique character and high importance of the SE Pacific stratocumulus regime (Li and Philander 1996).

In this study, mm-wavelength radar- and other remote sensing data as well as sounding and surface meteorological data collected during three research cruises form the basis for exploring clouds and boundary layer structures in this climate sensitive area. Section 2 includes a short description of the routes followed by the research vessels each year and the instrumentation onboard. Cruise-composite thermodynamic and cloud structures are presented and compared in section 3, in terms of cloud boundaries, inversion strength and height, and vertical mixing. An outline of the proposed future work is briefly given in section 4.

2. 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), the ship campaigns to maintain and replace the buoy have been providing atmospheric researchers with the necessary means to deploy remote sensors and other instrumentation and conduct observations to improve our knowledge of the various processes associated with the SE Pacific stratus deck. The

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Stratus 2003 and Stratus 2004 research cruises served as part of the PACS/EPIC enhanced monitoring and process studies implementation schedule, and provided – in combination with EPIC 2001 – a unique data set by capturing most of the properties, fundamental for studying and analyzing the complex features of stratocumulus clouds and MABL in the subtropical SE Pacific. These measurements also allow stratocumulus in this region to be compared 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 illustrated 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 completely different route. The EPIC 2001 cruise started from the Galapagos Islands, where the NOAA 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. For 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, exactly like EPIC 2001. 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 24, after 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 crucial comparisons between the three field experiments. The most important of these domains seems to be the Stratus ORS location, where the ships were stationed for 5 to 6 days each time. This study plans to focus on this location and take advantage of the unique 3-year dataset, to study and compare the day-to-day evolution of the cloud-topped boundary layer and attempt to extract the statistical characteristics of the basic cloud properties. The transect along 20°S from 75 to 85° W is also common with all three research cruises, and could be ideal for studying the evolution of the MABL in the transition from the deeper-ocean cold waters to the coastal warmer regime. 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.

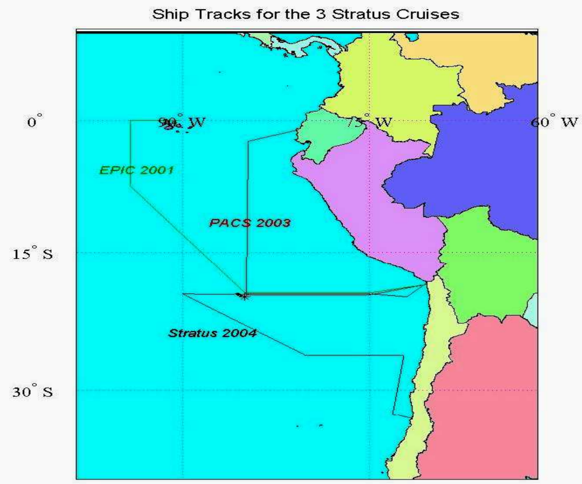

Fig. 1. The routes that the *Brown* and the *Revelle* followed during EPIC 2001, Stratus (or PACS) 2003 and Stratus 2004. The dark star indicates the location of the Stratus ORS buoy.

The EPIC 2001, Stratus 2003 and Stratus 2004 research cruises were collaborative efforts between various institutions and universities. An extensive suite of instruments was deployed onboard the research vessels for making measurements of boundary layer clouds and thermodynamic structure, surface fluxes and meteorology. The remote sensors that were used in each cruise and their respective products are briefly described in Table 1. All three cruises included a ceilometer, a 3-channel microwave radiometer and an 8.6-mm Doppler cloud radar (although the later suffered a component failure early in the Stratus 2004 cruise). Surface meteorology, turbulence and radiative flux measurements as well as aerosol spectrometer measurements provided a near surface complement to these remote sensing instruments. Rawinsondes were also launched during the three field experiments providing 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 new very high resolution but low sensitivity 3.2-mm Doppler cloud radar was only used during Stratus 2004.

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

Remote Sensor	Cruise	Technical Spec	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, variable cloud conditions were encountered, with a characteristic interchange between extensive periods of complete cloud cover, fractional cloudiness and clear-sky periods. A closer look at the data reveals qualitative differences in the MABL structure and cloud conditions from year to year. A well-mixed stratocumulus-capped boundary layer was observed throughout the entire EPIC 2001 cruise (Bretherton et al. 2004). The fact that few broken-cloud and nearly no clear-sky periods were reported is confirmed by the very high cruise-averaged ceilometer derived cloud fraction value (almost 90%). Conditions differed, however, during the Stratus 2003 cruise (Kollias et al. 2004). The MABL structure was characterized by the strong capping inversion and often well mixed vertical thermodynamic structure observed in 2001, 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 cloud coverage, with a reduced average cloud fraction (about 80%) with respect to EPIC 2001, and the rare presence of decoupled layers with shallow cumuli clouds, which were not observed before. Although most of the general features observed in 2003 were also present during Stratus 2004, the preliminary analysis of the data collected during the third cruise in the subtropical SE Pacific stratocumulus regime reveals further differences and interesting features with respect to the previous field experiments.

An illustration of the MABL mixing ratio structures from 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 first – somewhat unexpected – feature observed regarding Stratus 2004 is the significant height increase of the sharp inversion that capped the MABL while the *Brown* remained stationed. This was not encountered in the respective period during EPIC 2001 and Stratus 2003, when the boundary layer depth remained approximately constant. 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), but its gradual increase resulted in an all-year ORS-location high about three days later, reaching 1.7 km – a value that remained almost constant for the remaining two days of the period. After the ship left 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. These higher boundary layer depths are significant given that the maximum inversion heights observed during EPIC 2001 and Stratus 2003 did not exceed 1.4 km. The inversion height increase is usually associated with a weakening of the subsidence above the inversion layer (Klein and Hartmann 1993), and therefore some of the future work should involve the collection and cross-analysis of the NCEP- or ECMWF-predicted vertical velocity in our attempt to explain the observed pattern.

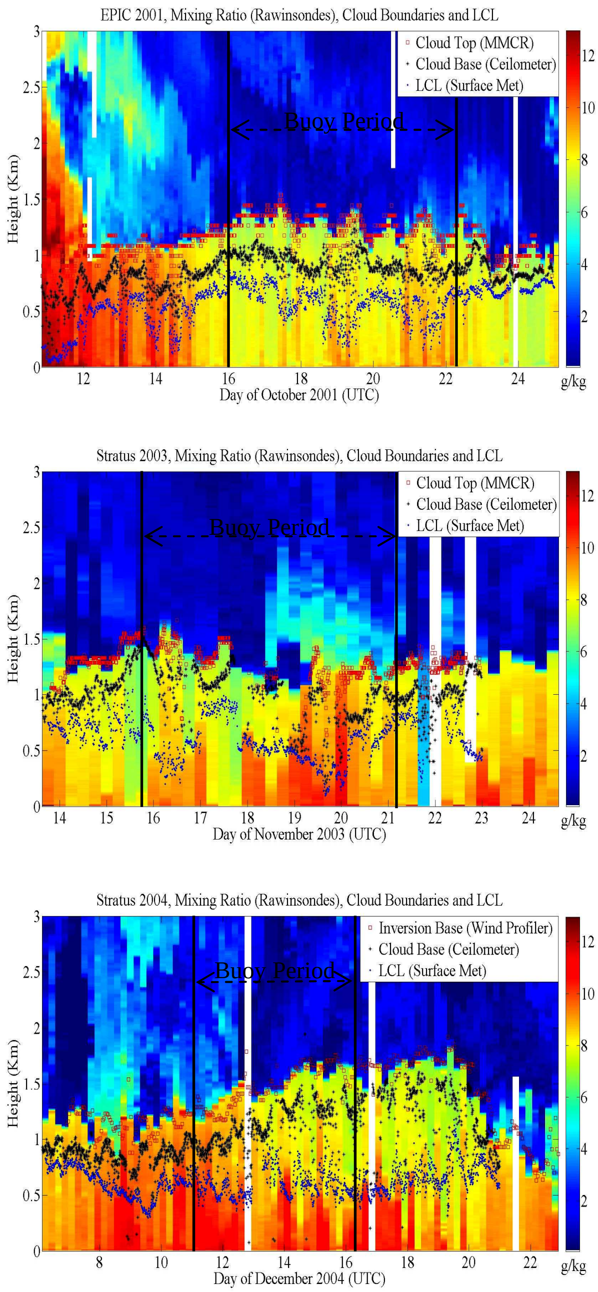

Fig. 2. Time-height mapping of mixing ratio r (g/kg) from the soundings launched during EPIC 2001 (upper panel), Stratus 2003 (middle panel) and Stratus 2004 (lower panel). The cloud boundaries and the LCL are also displayed. The cloud top (red) is retrieved from the MMCR for EPIC and Stratus 2003, while 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.

The vertical expansion of the MABL during Stratus 2004 did not, however, result in an equivalent increase of cloud thickness, as the ceilometer-derived cloud base height also increased with the course of time at the mooring location (lower panel, Fig. 2). A strong diurnal cycle of the cloud base height can also be observed, which does not seem to be accompanied by a respective pattern for the inversion base height, maybe due to the low frequency of the sounding launches. Such a pronounced cloud base diurnal cycle was not encountered during EPIC and Stratus 2003 and should be further investigated.

Another notable feature of the MABL structure during Stratus 2004 is the strong vertical gradients of moisture observed after December 13, which seem to highly correlate with the height increase of the inversion discussed above. These gradients in association with the time-height profile of the LCL indicate that the subcloud layer remains “decoupled” for several days. This means that the processes involved in the generation and maintenance of the stratus clouds are partially disconnected from the surface temperature and moisture fluxes. This decoupling, the extent of which is observed for the first time in this regime, seems to begin the third day that the *Brown* is stationed at the buoy location and is actually enhanced during the southeasterly route that was followed afterwards. The decoupling also seems to result in a decrease of the cloud thickness and the intermittent presence of shallow cumuli clouds below the high stratocumulus cloud base. Signs of this are indicated by the ceilometer cloud base estimates (black dots near 600-800 m in the lower panel of Fig. 2). The daily plots of the ceilometer backscatter intensity and cloud base height were evaluated against the respective plots of the FMCW reflectivity data (not shown here), and the comparison showed that some of the low-level returns in the cloud base profile are drizzle, while the rest can be nothing else other than low cumulus clouds.

4. FUTURE WORK

The differences discussed above between the MABL snapshots captured during the three major field experiments in the SE Pacific stratocumulus regime definitely add to the already-known complexity of the coupled atmospheric-ocean system in the region. Processes, such as cloud-top radiative cooling, entrainment of dry air above the inversion into the cloud layer, in-cloud circulation and turbulent mixing, and drizzle formation and evaporation beneath the cloud layer interact in a complex manner that makes it difficult to draw final conclusions on the kind and extent of influence that each one individually imposes on the lifecycle of stratus clouds. Under this context and in an attempt to better comprehend these processes and their interactions, our future work will focus on the development of an extensive description of marine stratocumulus macroscopic and microphysical properties and the investigation of their temporal (diurnal, seasonal and interannual) variability in association with the evolution and variability of the MABL thermodynamic structure.

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