2.5 STRATOCUMULUS AND CLIMATE: OBSERVATIONS FROM EPIC 2001

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1. INTRODUCTION

Overlaying the cool southeast Pacific Ocean is the most persistent subtropical stratocumulus deck in the world. These clouds are a source of significant negative radiative forcing, and they play a supporting role in the seasonal cycle of the East Pacific Ocean and El Niño-Southern Oscillation, but they have proven difficult for climate models to simulate. The EPIC 2001 stratocumulus (Sc) study conducted the first major in-situ investigation of cloud and boundary layer processes in this region. Its main goals were (1) to characterize the cloud and boundary layer structure, compared to the better studied northeast Pacific Sc region, (2) to investigate the importance of drizzle in regulating cloud thickness and albedo, and (3) to provide a context for understanding long-term measurements from a flux-reference buoy at 20°S, 85°W, and for testing and improving climate model parameterizations in Sc regions. Such parameterizations play key roles in determining the sensitivity of climate to anthropogenic perturbations because they determine cloud feedbacks on climate change.

Comprehensive ship-based remote sensing and surface measurements were taken during a two-week cruise aboard the NOAA research vessel *Ronald H. Brown* in October 2001. During the cruise, the ship was stationed near the IMET buoy at 20°S, 85°W for six days (the 'buoy period'). The ship track is shown in Figure 1. Ship-board instrumentation included three-hourly soundings, a scanning 5-cm and a vertically-pointing 8-mm radar, a lidar and microwave radiometer for examining clouds and precipitation, and measurements of aerosols and surface turbulent and radiative fluxes. A well-mixed boundary layer with a regular, pronounced diurnal cycle of cloud thickness and boundary layer depth was observed, modulated by an unexpectedly strong remotely-forced diurnal cycle of subsidence. Mesoscale organization of the cloud field, as seen in Figure 1, was ubiquitous. Nighttime drizzle was substantial except in the more polluted near-coastal region. This integrated dataset is attractive for comparisons with both climate and detailed process models.

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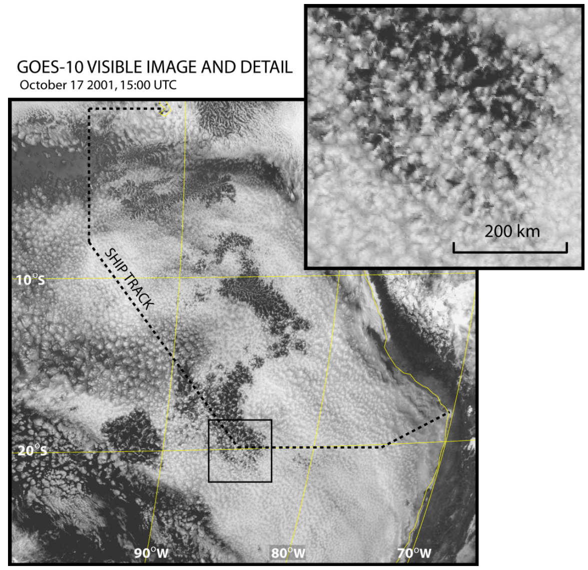

Figure 1: The southeast Pacific Sc region as viewed by GOES-East. The prominent dark patches of broken cloud in the center, surrounded by almost unbroken cloud cover, are a commonly seen but still mysterious feature of subtropical Sc, possibly associated with regions of enhanced drizzle. The inset zooms in on the mesoscale cellularity in the cloud field on 10-40 km scales.

2. BOUNDARY LAYER STRUCTURE AND THE DIURNAL CYCLE

Measurements during EPIC 2001 Sc revealed a boundary layer that was surprisingly well mixed. In comparable regions in the northeast Pacific, the boundary layer is decoupled, the capping inversion is weaker, and cumulus clouds grow below the Sc (Albrecht et al. 1995, Klein et al. 1995, Wyant et al. 1997). No cumulus were observed in the EPIC Sc study region in the southeast Pacific. Although the diurnal cycle is very strong in this region, the boundary layer remained relatively well-mixed and the inversion sharp throughout the day. The diurnal cycles of potential temperature and mixing ratio in and above the Sc boundary layer are shown as

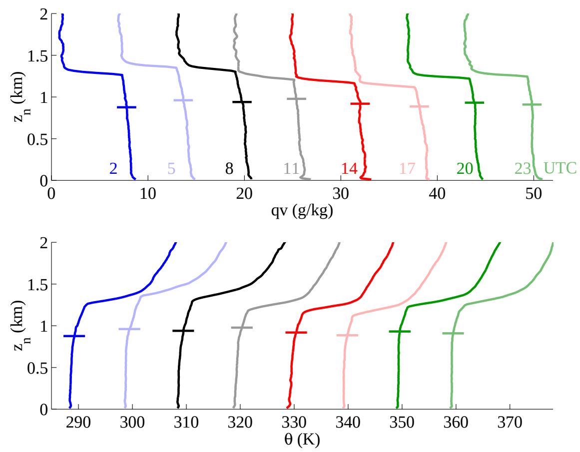

Figure 2: Buoy-period diurnal cycle of six-day composite mixing ratio and potential temperature soundings. Horizontal lines indicate mean ceilometer-derived cloud base. Offsets of 6 g kg^{-1} and 10 K are applied to successive 3-hourly profiles.

profiles composited over six days in Figure 2. The figure shows that the cloud base does not vary significantly during the day, but the inversion base, or cloud top, rises at night and lowers during the day (Bretherton et al. 2003).

There are two methods by which the diurnal cycle is a modulates cloud thickness in southeast Pacific Sc. Nighttime longwave cooling drives increased mixing throughout the boundary layer, increasing cloud-top entrainment. This raises the cloud top, thickening the cloud. The other reason for higher inversion heights at night is decreased nighttime subsidence, depicted in Figure 3. This figure shows a diurnal composite of ECMWF subsidence over the six-day observational period near the IMET buoy (Bretherton et al. 2003).

Figure 3 also shows the diurnal cycle of cloud fraction, with highest cloud amount occurring during the night, and lowest during the early afternoon, when short-wave forcing is greatest, following the cycle of cloud thickness. Liquid water path (LWP) from the microwave radiometer is also plotted, showing that actual values agree well with adiabatic calculations based on cloud thickness. Via the liquid water path, the diurnal cycle also greatly influences drizzle falling from the Sc, with most drizzle events occurring at night or in the early morning.

3. DRIZZLE AND AEROSOLS

The southeast Pacific Sc boundary layer is exceptionally dry relative to other oceanic regions, but numerous drizzle events were experienced during

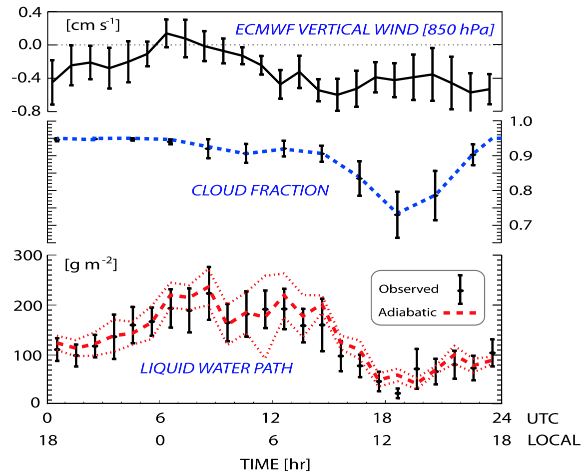

Figure 3: The buoy-period mean diurnal cycle of (top) ECMWF-predicted vertical velocity from hourly sampling of 12-36 hour operational forecasts, (middle) ceilometer-derived cloud fraction, and (bottom) liquid water path derived from the shipboard microwave radiometer and adiabatic liquid water path derived from cloud thickness. Vertical bars show the standard deviation of hourly average values on individual days from the six-day hourly mean.

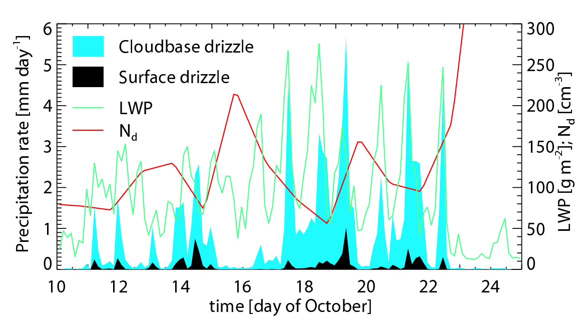

Figure 4: Retrievals of hourly-averaged drizzle rate, liquid water path (LWP), and cloud droplet concentration N_d from a combination of ship-based remote sensors.

EPIC 2001. Both radars observed considerable drizzle while the ship was on station at 20°S 85°W. Taking into account several sources of uncertainty, Comstock et al. (2003) estimated the amount of drizzle falling from the cloud base, and the amount reaching the surface, to within a factor of 2-3. These time series are shown in Figure 4. Approximately 85% of the precipitation evaporates in the boundary layer.

With so little precipitation reaching the sea surface, drizzle is not a significant factor in the boundary-layer water budget. Instead, its indirect effects are important to the structure and dynamics of the boundary layer. The clouds are warmed by condensation while the sub-cloud layer is cooled by the evaporation of drizzle. This serves to stratify the boundary layer, suppressing turbulence and therefore cloud-top entrainment. Reduced mixing leads to increased vertical moisture gradients and a more horizontally inhomogeneous cloud layer (Stevens et al. 1998).

Figure 4 also shows the time series of the microwave-radiometer-derived LWP and estimated cloud droplet concentration, N_d. The latter was derived using daytime downwelling solar radiation (see Bretherton et al. 2003). Drizzle is strongly tied to the diurnal variations of LWP. Larger drizzle rates also tend to correspond to periods of lower droplet concentration, or 'cleaner' clouds. Closer to the South American coast (October 22-25) N_d rose, indicative of 'dirtier' cloud conditions. No drizzle was observed on these days. UNAM condensation nucleus measurements aboard the ship are also consistent with these findings (Bretherton et al. 2003).

4. COMPARING OBSERVATIONS WITH MODELS

Prior to the EPIC Sc field project, there were few observations of the cloud and boundary layer structure in the southeast Pacific. Observations from this campaign, then, serve as useful comparisons with general circulation models (GCMs). Figure 5 shows profiles of liquid water content (LWC), mixing ratio and potential temperature from observations, reanalyses and models. The observation profiles were derived from six-day mean soundings (except for the LWC, which was estimated assuming a linear increase of liquid water between cloud base and cloud top; see Bretherton et al. 2003). ECMWF and NCEP observational analyses are also six-day means. Grid-point average October climatologies are shown from two GCMs - NCAR's Community Atmosphere Model version 2.0 (http://www.ccsm.ucar.edu/models/atm-

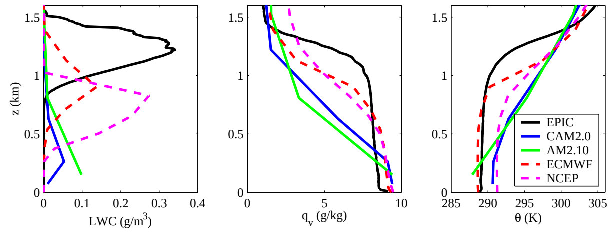

Figure 5: Comparison of six-day buoy-period mean cloud and thermodynamic profiles from EPIC with ECMWF and NCEP operational analyses for the same time and location, and with October climatological profiles for recent versions of two leading general circulation models.

cam) and GFDL's Atmospheric Model version 2.10 (Anderson et al. 2003).

Although an exact comparison among all of the profiles is not possible, given their differing time scales, Figure 5 exposes the shortcomings of the current parameterizations in dealing with the complex interactions in the Sc boundary layer. The EPIC Sc observational period is representative of October climatology in all parameters except for the LWP, which was approximately 30% higher than satellite October-mean estimations (Wood et al. 2002). Even so, both the CAM2.0 and AM2.10 models significantly underestimate the liquid water path and the inversion height. Because the cloud occurs so close to the surface, drizzle and numerical diffusion are likely to be the sole regulators of cloud thickness (Bretherton et al. 2003).

5. CONCLUSIONS

The EPIC Sc dataset provides a wealth of information about the southeast Pacific stratocumulus boundary layer. It documents the strong diurnal cycle, sharp inversion, and frequent drizzle present in this region. Results suggest that, while entrainment is more responsible for variations in cloud thickness, drizzle affects the horizontal inhomogeneity, or cellularity, of the cloud layer. The data show that decreased droplet concentration, or 'cleaner' cloud conditions, correspond to increased drizzle, but the full feedback between aerosols, cloud structure and lifetime is yet to be resolved. Using the observed cloud properties, future modeling studies will be better able to untangle the links between aerosols, drizzle, mesoscale cloud variability, and cloud albedo.

The southeast Pacific stratocumulus boundary layer is an important player in ENSO and future climate change, so it is important for climate models to correctly capture the processes taking place there. Observations from EPIC Sc, as well as ongoing data from the IMET buoy, are valuable tools for model comparisons.

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