The 1997 Pan American Climate Studies Tropical Eastern Pacific Process Study. Part II: Stratocumulus Region*

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ABSTRACT

An ad hoc experiment in the marine stratocumulus region to the west of Mexico was conducted from 29 August to 6 September 1997 as part of the Pan American Climate Studies Tropical Eastern Pacific Process Study cruise on the National Oceanic and Atmospheric Administration ship *Ronald H. Brown* after a medical emergency cut short the planned time in the eastern Pacific ITCZ. The joint variation of cloud structure, drizzle, and tropospheric stratification was documented by a combination of three hourly upper air soundings, scanning C-band radar, hourly cloud photography, and visual observation. The sensitive C-band Doppler radar mounted on the ship was able to obtain observations of drizzle cells with regions of greater than 10 dBZ of 2–3-km scale in the horizontal and peak reflectivities of greater than 25 dBZ.

1. Introduction

The marine stratocumulus[1] portion of the Pan American Climate Studies (PACS) Tropical Eastern Pacific Process Study (TEPPS) cruise and its objective to characterize drizzle in these clouds were conceived during the medical evacuation transit from the ITCZ to San Diego as an ad hoc use of the ship and its instruments for the remaining 8 days of ship time. Since TEPPS was designed as an ITCZ experiment, the ship was not equipped with many of the instruments typically used in marine stratocumulus studies (e.g., aerosol measuring systems and millimeter wavelength radars). On the other hand, we saw an opportunity to make a feasibility study for the use of a sensitive C-band precipitation radar to detect and characterize drizzle in a stratus layer. The ship had sufficient radiosondes remaining onboard to launch soundings every 3 h so that the thermodynamic and moisture stratification could be monitored along with the radar observations. Hourly cloud photography in daylight hours and visual observations of the sky further enhanced the dataset. From these three primary sources of information, the joint variation of cloud structure, precipitation (i.e., drizzle), and stratification were monitored for 8 days. In addition, the Doppler radial velocities measured by the radar allowed us to assess the dynamics of the drizzle-producing mechanisms within the stratus. These measurements will aid in improving the representation of marine stratus drizzle in models and open a new research direction in which sensitive precipitation radars are added to the tools used to study oceanic stratus.

In contrast to the ITCZ, which is a manifestation of the rising branch of the Hadley circulation, the marine stratus region is characterized by large-scale atmospheric subsidence associated with the descending branch of the Hadley circulation. Large-scale subsidence, low-level stratus clouds, sea surface tem-

[1]The cloud-topped boundary layer contains both stratus and stratocumulus clouds. For simplicity these terms will be used interchangeably except in reference to particular cloud types in photographs.

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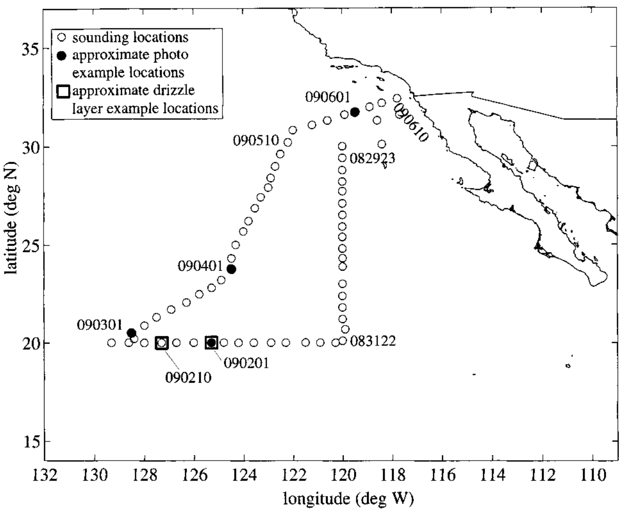

FIG. 1. Locations of GPS soundings during marine stratus portion of the TEPPS cruise. Locations of photos and upper air soundings in Figs. 4 and 6 are indicated.

perature, atmospheric turbulence, and radiation interact with one another to maintain a persistent, strong inversion separating the boundary layer from the free atmosphere (Albrecht 1989; Rogers et al. 1995). The distribution and amount of drizzle within marine stratus clouds have important implications since numerical models often assume that θ_e and total water are conserved (Wyant et al. 1997). Our ad hoc objectives in the marine stratus region were to map the nature and areal extent of the marine stratocumulus drizzle in the vicinity of the ship using C-band radar and to characterize the associated atmospheric and upper-ocean environment.

There have been few quantitative observations of drizzle in marine stratus. Short-lived, spatially small drizzle cells are difficult to sample well with aircraft and vertically pointing radars. A scanning 8.66-mm-wavelength radar was used in the Atlantic Stratocumulus Transition Experiment (ASTEX) to study the characteristics of clouds in the marine stratus to trade cumulus transition region near the Azores (Albrecht et al. 1995). Stratocumulus clouds in the Azores containing drizzle had radar reflectivities > –15 dBZ while clouds without drizzle had reflectivities < –15 dBZ (Frisch et al. 1995). Millimeter wavelength radars such as those used in ASTEX become attenuated when reflectivities are > ~22 dBZ, detecting the presence but not the structure of regions with larger drizzle drops and higher drop concentrations. The longer wavelength of the C-band radar does not detect cloud drops but can characterize the structure of regions containing drizzle drops. The scanning C-band Doppler radar on the ship during TEPPS made possible the collection of volumetric snapshots of the microphysical and velocity structure of drizzle cells. These data provide information on the growth of drizzle within and below the cloud layer and on circulations within drizzle-containing clouds.

2. Ship-based observations

The atmospheric and upper-ocean instrumentation for the TEPPS cruise on the National Oceanic and Atmospheric Administration (NOAA) ship *Ronald H. Brown* is described in Yuter and Houze (2000). For the stratocumulus portion of the cruise, the ship followed a polygon track starting from and ending at San Diego (Fig. 1 and dashed line in Fig. 4 of Yuter and Houze 2000). The exact track was based on the location of the stratocumulus cloud deck seen in visible satellite data at the time the ship was in the area (Fig. 2). The observations of stratocumulus clouds were primarily made between 20° and 30°N. This area is south of the region investigated during the marine-stratocumulus portion of the First ISCCP Regional Experiment (FIRE; Cox et al. 1987).

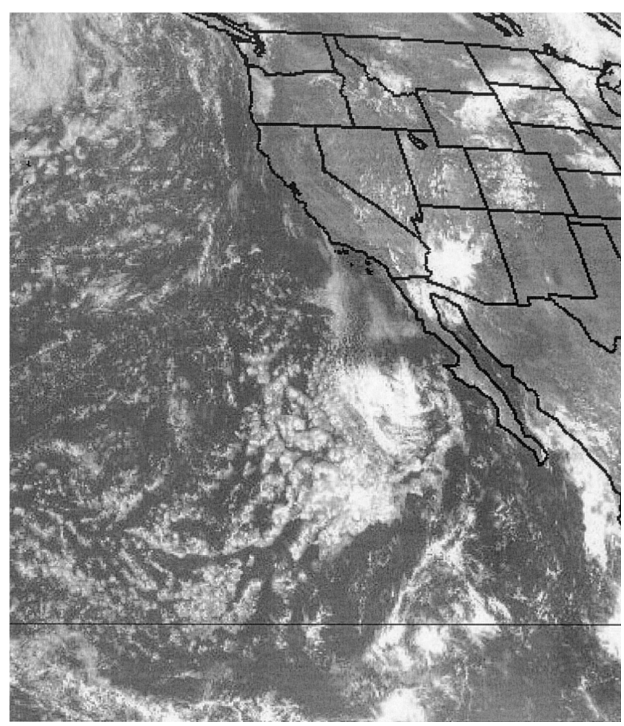

FIG. 2. GOES VIS image of western North America and the eastern Pacific from 1800 UTC 1 Sep 1997 showing the stratocumulus cloud field.

TABLE 1. Marine stratocumulus radar scan strategy.

Scan name	Gate spacing (m)	PRF (Hz)	Usable range (km)	Scan rate (°s^{-1})	Elevation angles (°)
Surveillance	250	300	240*	12	0.4, 0.8
Sc volume scan	125	1200	25**	20	3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.00,12.0, 13.0

*Although technically the maximum possible range at 300 Hz post repetition frequency is 500 km, the height of the center of the 0.4° elevation scan beam would be 18 km above sea level at this range. A more practical usable range for detection of precipitation echoes is 240 km. At 240-km range, the 0.4° elevation scan beam center is at 5-km altitude and the beam is 6.2 km wide.
**The stratus cloud layer was usually between 1- and 2-km altitude. Transmitter leakage contaminated the first few gates of reflectivity. A 3° elevation beam is at 1.3-km altitude at 25-km range.

Observational strategy modifications for the stratocumulus region

The observational strategies for the stratocumulus region were modified from those used in the ITCZ portion of TEPPS (Yuter and Houze 2000) to optimize the collection of data in a shallow stratus cloud regime. A radar volume scan strategy was redesigned to obtain high resolution measurements within a low cloud deck from 1 to 2 km in altitude (Table 1). Surveillance scans were made at 0 and 30 min after the hour and volume scans were made four times per hour. Upper air soundings were launched every three hours corresponding to ~70 km distance along the ship track (Fig. 1). The amount of helium in the balloons was reduced compared to the TEPPS ITCZ launches in order to slow the sonde ascent and thus maximize the vertical resolution within the boundary layer. The vertical resolution of the NOAA Aeronomy Laboratory 915-MHz (Carter et al. 1992; Gage et al. 1994; Carter et al. 1995) and S-band profilers (Ecklund et al. 1995) was increased compared to the ITCZ observations. Both profilers were operated alternately with 105- and 60-m pulse lengths up to 6.7- and 3.8-km altitude respectively (Table B1 in Yuter and Houze 2000). To characterize the upper ocean structure beneath the stratus clouds, CTD (conductivity, temperature, and depth) profiles to 300-m depth were obtained at 0930 and 1530 local time.

3. Drizzle in eastern Pacific marine stratocumulus

a. Stratus clouds and drizzle

During June through August, marine stratus clouds typically occur over 55% of the time within the region from 20° to 30°N and 120° to 130°W (Fig. 3; Warren et al. 1986, 1988). Stratocumulus clouds were present on the westward and northeastward legs of the polygonal track off the west coast of Mexico (Figs. 1 and 2) in early September 1997. From 1900 UTC 29 August to 1200 UTC 6 September 1997 half of the hourly

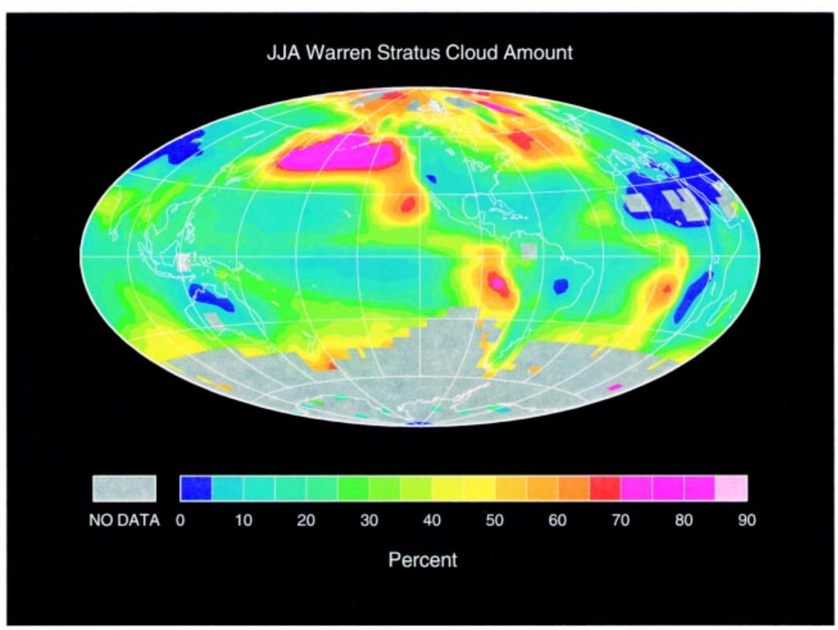

FIG. 3. Global map of Jun–Jul–Aug average stratus cloud amount derived from Warren et al. (1986, 1988) cloud atlas data. (From Klein and Hartmann 1993.)

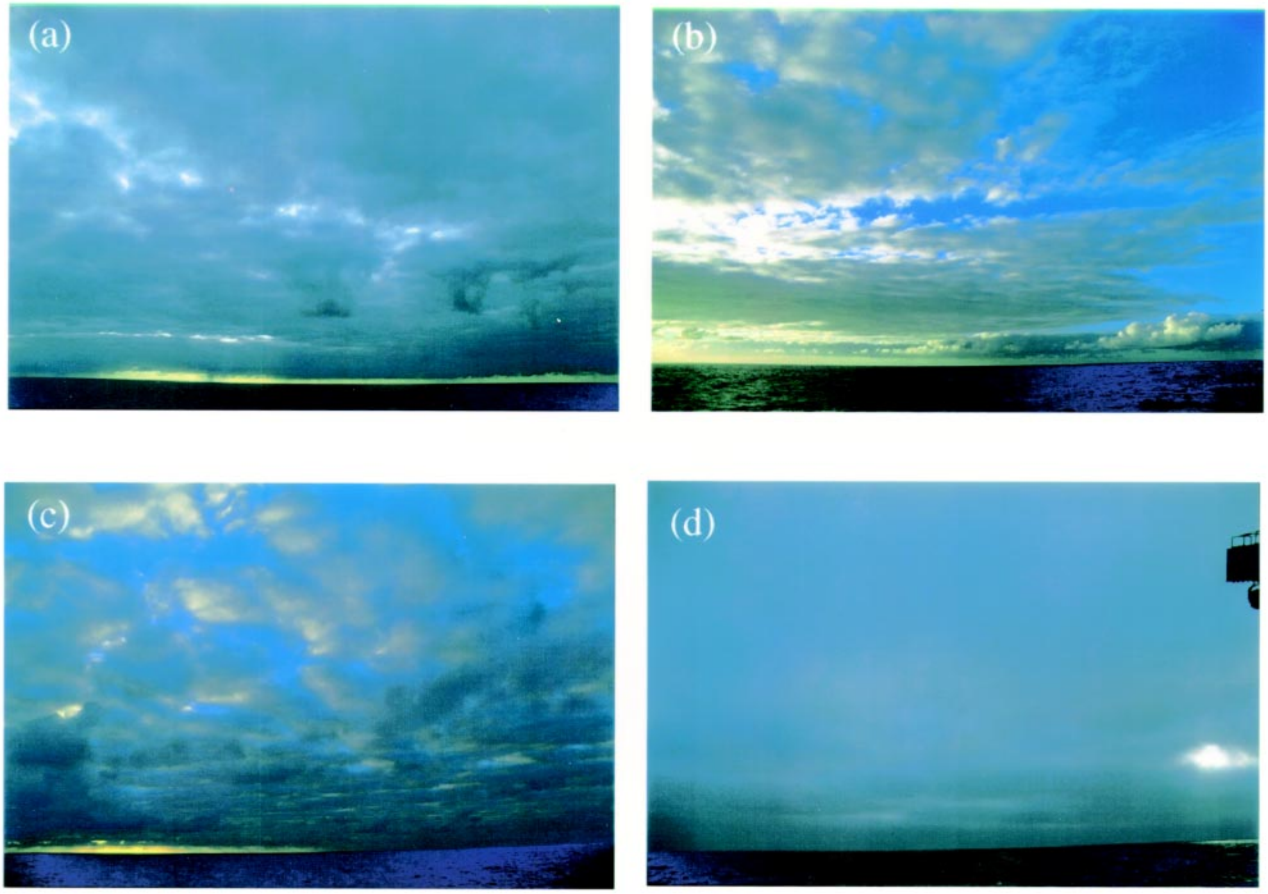

FIG. 4. Photographs of clouds within the marine stratocumulus region. Locations are indicated in Fig. 1: (a) 0100 UTC 2 Sep 1997 showing stratocumulus with some downward protruding scud, (b) 0200 UTC 3 Sep 1997 showing stratocumulus and cumulus (note base height), (c) 0200 UTC 4 Sep 1997 showing stratocumulus and cumulus (note base height), and (d) 0100 UTC 6 Sep 1997 stratus deck near shore.

daytime cloud type observations (World Meteorological Organization 1975) made from ships were $C_L = 5$, "stratocumulus not resulting from the spreading out of cumulus," and half were $C_L = 8$ "cumulus and stratocumulus other than that formed from the spreading of cumulus; the base of the cumulus is at a different level than that of the stratocumulus."

A set of cloud photographs in Fig. 4 taken from 1800 to 1900 local time indicate the range of cloud conditions seen along the ship track in the stratocumulus region. The low sun angle near sunset makes identification of falling drizzle easier. Figure 1 indicates the location of these photographs along the ship track. Near 20°N, 125°W at 0100 UTC 2 September 1997 (Fig. 4a) stratocumulus clouds were present with low hanging scud. A wide drizzle region obscured the horizon on the left edge of the photo and a narrow drizzle region was to the right of center. Close to the western edge of the stratocumulus region, the cloud deck at 0200 UTC 3 September had more breaks (Fig. 4b). Both stratocumulus and cumulus clouds were present and both appear to have had bases at similar levels. No drizzle was evident. Near 24°N, 124°W both cumulus and stratocumulus clouds were present with the cumulus clouds below the stratocumulus deck (Fig. 4c). On the right side of the picture drizzle obscured the horizon. Close to San Diego at 0100 UTC 6 September (Fig. 4d), the stratus deck was thick and almost continuous with sun breaking through a patch to the right of the photograph. The visual appearance of the clouds was consistent with the upper air sounding data. The rain rates of drizzle falling to the surface were too low to be detected by most of the automatic rain measurement instrumentation onboard ship. The Institut für Meereskunde optical disdrometer (Grossklaus et al. 1998) detected drizzle but could not characterize its drop size distribution. Six samples of drizzle falling on the ship were

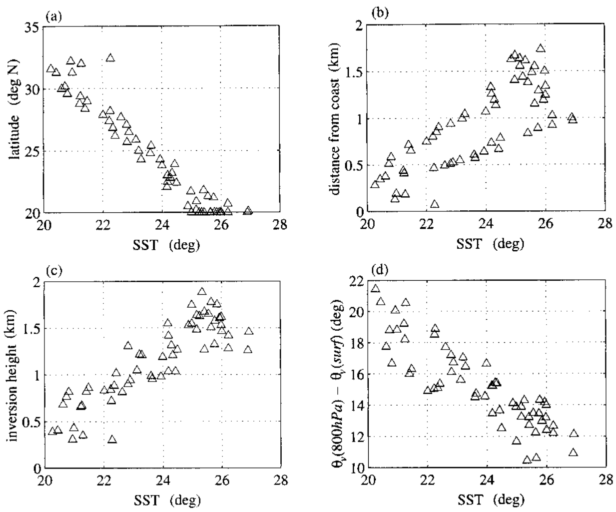

FIG. 5. Boundary layer characteristics derived from upper air soundings and coincident surface measurements within the marine stratocumulus region. Plots of sea surface temperature versus (a) latitude, (b) distance from coast, (c) inversion height z_i, and (d) inversion strength [θ_v (800 hPa) – θ_v (surf)].

obtained with filter paper (Rinehart 1995). The filter paper method cannot detect drops smaller than 0.4 mm in diameter. Of the drops detected, most were in the 0.4- and 0.6-mm size categories but a few drops as large as 1.2-mm diameter were observed.

b. Vertical structure of the lower troposphere within marine stratocumulus

The use of Global Positioning System (GPS) sondes yielded upper air sounding data with a vertical resolution of 30 m, comparable to aircraft in situ measurements. The locations of the upper air soundings along the ship track are shown in Fig. 1. In concurrence with previous studies (Neiburger 1960; Neiburger et al. 1961), our data show that the height of the top of the inversion is both a function of distance from the coastline and latitude. One of the primary factors determining boundary layer characteristics in the stratocumulus region is sea surface temperature. In the region traversed during the cruise, coastal upwelling off the coast of Baja California superimposed a pattern of decreasing sea surface temperature with decreasing distance from the coast on top of a general increase in temperature of 6°C between 30° and 20°N (Figs. 5a and 5b). Both the height of the inversion and the strength of the inversion, as indicated by the difference in θ_v at 800 hPa and the surface, were directly related to sea surface temperature (Figs. 5c and 5d). Warmer surface temperatures enhance the buoyancy production term of the turbulent kinetic energy budget and act to increase the height of the inversion. The strength of the inversion increases as SST decreases mainly because of colder surface potential temperatures relative to those at the 800-hPa level. Subsidence warming, which acts to increase the 800-hPa virtual temperature, further enhances the contrast between the 800-hPa and surface temperatures and hence the inversion strength.

The lower portion of the upper air soundings exhibited an evolving structure after sunset and later during the night (Fig. 6), as seen in previous observations of cloud-topped marine boundary layers (Betts 1990; Rogers et al. 1995). At 0132 UTC (1832 LT) on 2 September 1997, the cloud layer was shallow and extended from the bottom of the inversion to 850 hPa (Fig. 6a). The weak temperature inversion and drying at 925 hPa indicated a thermally stable interface between the cloud and subcloud layers, which decoupled these layers in terms of turbulent exchange of heat and moisture. The 30-m resolution of the sounding data resolved a 200-m deep transition layer between the surface mixed layer below and the cloud layer above, similar to that observed by aircraft data during the Frontal Air–Sea Interaction Experiment near Bermuda (Rogers 1989). The mechanism for the decoupling evident in this sounding is more likely shortwave heating of the cloud layer rather than advection of warm boundary layer air above the surface layer since boundary layer winds were from the north to northeast. Nine hours later at 1038 UTC (0338 LT), the cloud layer

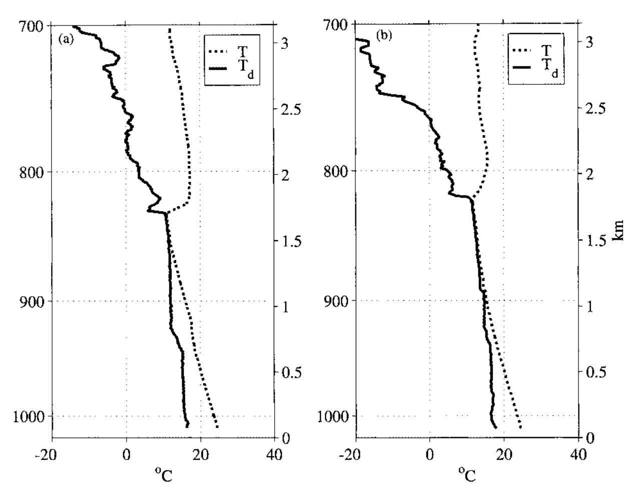

FIG. 6. Example of upper air soundings showing boundary layer characteristics just after sunset and later in the evening: (a) 0132 UTC 2 Sep and (b) 1038 UTC 2 Sep. T = temperature and T_d = temperature dewpoint. Vertical scale is in hPa. Positions of soundings within the marine stratocumulus region are indicated in Fig. 1.

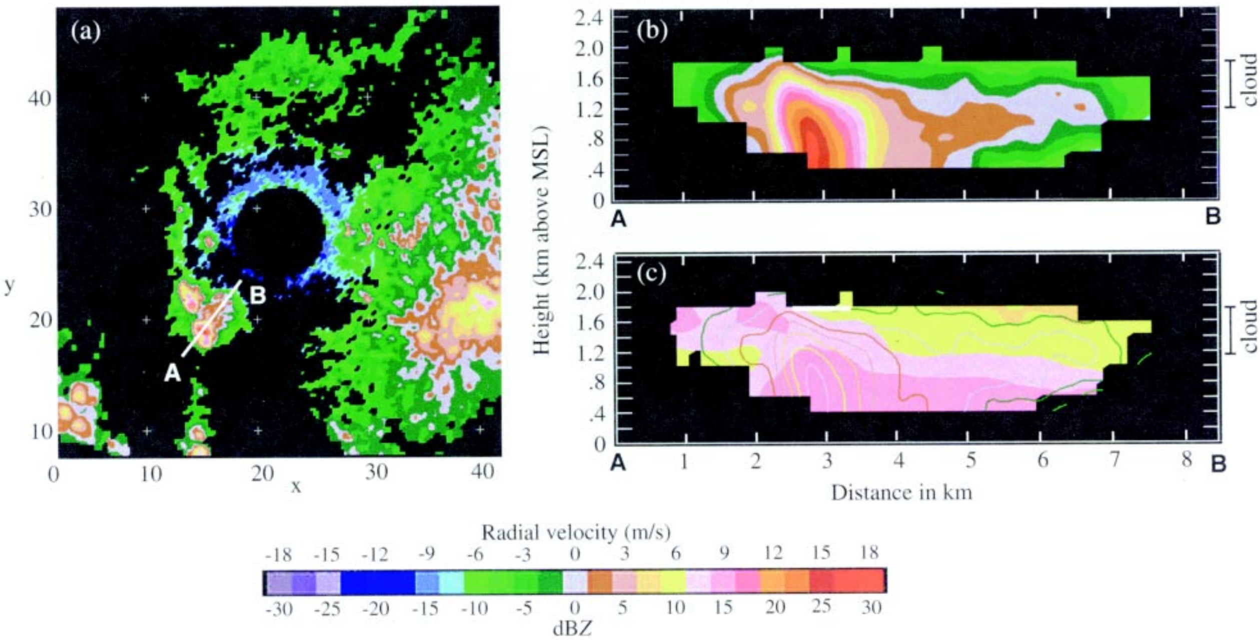

FIG. 7. Ship-based C-band radar data within the marine stratocumulus region. Interpolated three-dimensional volume data from 0320 UTC 2 Sep 1997. (a) Horizontal cross section of radar reflectivity at 1-km altitude, (b) vertical cross section of radar reflectivity along line A–B in (a), and (c) vertical cross section of radial velocity along line A–B in (a) with radar reflectivity contours overlain. Reflectivity contours in (c) are every 5 dBZ starting at −10 dBZ. The radar reflectivity color bar in the figure is centered on 0 dBZ to reveal the structure of the weak reflectivities within the stratocumulus clouds. The resolution of the interpolated volume is 0.25 km in the horizontal and 0.2 km in the vertical.

had thickened downward to 900 hPa and the earlier decoupling had mixed out. Such nighttime deepening of the cloud layer was typical of the cloud layers observed in the stratocumulus region.

c. C-band radar observations within marine stratus

The C-band radar volumes collected within the stratocumulus region provide three-dimensional snapshots of the structure of the drizzle within the cloud layer. The reflectivity and radial velocity data were interpolated using National Center for Atmospheric Research REORDER software to a Cartesian grid covering 40.25 km × 40.25 km in the horizontal with 0.25-km spacing and 0-3.2-km MSL in the vertical with 0.4-km spacing. Figure 7a shows the horizontal radar reflectivity structure at 1-km altitude within 20 km of the ship at 0320 UTC (2030 LT) on 2 September, roughly two hours after the sounding in Fig. 6a. The 1-km altitude is below the cloud layer indicated in the sounding so the enhanced reflectivity structures are drizzle falling below cloud. Two small cells ~12 km southwest of the ship have reflectivities up to 25 dBZ. A vertical cross section through one of the cells (Figs. 7b,c) shows the portion of the cell > 0 dBZ to be roughly 5.5 km wide and the region > 10 dBZ (likely corresponding to heavier drizzle) to be about 2 km in horizontal dimension. Since the radar beams are nearly horizontal, the radial velocity along a radial from the radar corresponds to horizontal velocity. Weak divergence is evident near the top of the > 10 dBZ reflectivity region within cloud at $d = 2.6$ km along the cross section (Fig. 7c).

Several hours later at 1035 UTC (0335 LT) on 2 September 1997, there were many more small drizzle cells in the vicinity of the ship (Fig. 8a). The cross section in Fig. 8 corresponds to the sounding data in Fig. 6b. Since the cloud had thickened downward, 1-km altitude was now near the bottom of the cloud layer. Small cells were more numerous near the ship, and 25-dBZ intensities were more prevalent than they were at 0320 UTC (2030 LT). The vertical cross section in Fig. 8b shows the structure of several cells within a general region of very weak reflectivity. The cells defined by the 10-dBZ threshold were ~2–3 km in scale. The height of the local maxima in reflectivity varied from 1-km altitude in the cells at $d = 7$ km and 34 km to 0.6-km altitude in the cell at $d = 28$ km. The cell at $d = 34$ km penetrated the inversion indicated in the sounding to mix with the free atmosphere

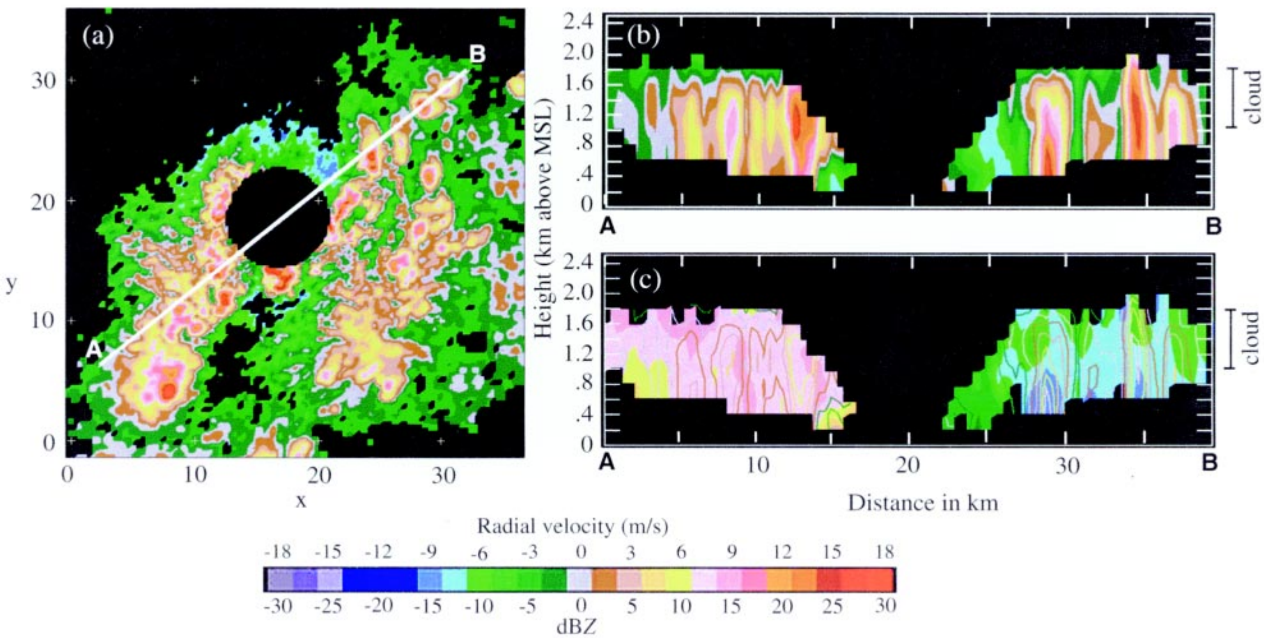

FIG. 8. Ship-based C-band radar data within the marine stratocumulus region. Interpolated three-dimensional volume data from 1035 UTC 2 Sep 1997. (a) Horizontal cross section of radar reflectivity at 1-km altitude, (b) vertical cross section of radar reflectivity along line A–B in (a), and (c) vertical cross section of radial velocity along line A–B in (a) with radar reflectivity contours overlain. Reflectivity contours, color bar, and interpolated volume resolution as in Fig. 7.

above. The varying heights of the maximum reflectivity within different cells probably corresponded to small cells in different stages of their life cycles. Divergent radial velocity is indicated at 1.2-km altitude near the top of the > 10 dBZ region of the cell at distance $d = 28$ km. The three weaker reflectivity cells between $d = 2$–8 km had their stronger reflectivities at or slightly above the cloud base of 1-km altitude.

The peak observed reflectivities within these drizzle cells were significantly higher than those observed by 3-mm wavelength airborne radar off the coast of Oregon (Vali et al. 1998) and by 8.66-mm wavelength radar during the Atlantic Stratocumulus Transition Experiment (ASTEX; Frisch et al. 1995). From the reflectivity data alone one might conclude that these data were obtained in cumulus clouds, yet visual observation of the clouds clearly indicated stratocumulus rather than cumulus clouds (e.g., Fig. 4a). This apparent discrepancy suggests that stratocumulus drizzle may vary in intensity from region to region.

Since scanning precipitation radars have not been previously used to examine marine stratus drizzle, radar reflectivity to liquid water content (*Z–M*) and reflectivity to rain rate (*Z–R*) relationships are not available in the published literature. Drop-size data have been collected using optical 2D probe technology in subtropical marine stratus, most recently in the ASTEX project near the Azores. We are working to obtain these and similar data from FIRE to derive appropriate *Z–R* and *Z–M* relations for marine stratus drizzle. When future field studies plan the use of C-band radar to map the three-dimensional structure of drizzle, airborne microphysical measurements of the drop-size spectra in the same region and within the same type of clouds should be included and analyzed to yield suitable *Z–M* and *Z–R* relations, since drop spectra characteristics may vary between regions.

4. Conclusions

The PACS TEPPS cruise was originally designed as an ITCZ experiment (Yuter and Houze 2000). A medical evacuation cut short the planned time in the ITCZ but afforded the opportunity to use the precipitation radar and upper air sounding system on the NOAA ship *Ronald H. Brown* to examine the marine stratocumulus region to the west of Mexico from 29 August to 6 September 1997.

A sensitive C-band Doppler radar was successfully used to observe drizzle distribution and structure within marine stratocumulus clouds. Drizzle layers within stratocumulus clouds to the west of Mexico in early September 1997 contained three-dimensional drizzle cells with regions > 10 dBZ of ~2–3 km in horizontal dimension and divergent radial velocities at cell top. Once appropriate *Z–R* relations for these regions are developed, drizzle amounts can be derived and used to address water budgets within stratocumulus clouds. In future marine stratocumulus studies, volumetric data from a scanning C-band radar would complement the millimeter radars that are usually used to study stratocumulus clouds but become attenuated in drizzle.

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