A Revised Conceptual Model of the Tropical Marine Boundary Layer. Part III: Bragg Scattering Layer Statistical Properties

JENNIFER L. DAVISON, ROBERT M. RAUBER, AND LARRY DI GIROLAMO

Department of Atmospheric Sciences, University of Illinois at Urbana–Champaign, Urbana, Illinois

MARGARET A. LEMONE

National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

This paper examines the structure and variability of the moisture field in the tropical marine boundary layer (TMBL) as defined by Bragg scattering layers (BSLs) observed with S-band radar. Typically, four to five BSLs were present in the TMBL, including the transition layer at the top of the surface-based mixed layer. The transition-layer depth (~350 m) exhibited a weak diurnal cycle because of changes in the mixed-layer depth. BSLs and the “clear” layers between them each had a median thickness of about 350 m and a lifetime over the radar of 8.4 h, with about 25% having lifetimes longer than 20 h. More (fewer) BSLs were present when surface winds had a more southerly (northerly) component. Both BSLs and clear layers increased in depth with increasing rain rates, with the rainiest days producing layers that were about 100 m thicker than those on the driest days. The analyses imply that the relative humidity (RH) field in the TMBL exhibits layering on scales observable by radar. Satellite and wind profiler measurements show that the layered RH structure is related, at least in part, to detraining cloudy air.

Based on analyses in this series of papers, a revised conceptual model of the TMBL is presented that emphasizes moisture variability and incorporates multiple moist and dry layers and a higher TMBL top. The model is supported by comparing BSL tops with satellite-derived cloud tops. This comparison suggests that the layered RH structure is related, in part, to cloud detrainment at preferred altitudes within the TMBL. The potential ramifications of this change in TMBL conceptualization on modeling of the TMBL are discussed.

1. Introduction

The structure of the tropical marine boundary layer (TMBL) has been an important area of research for the last half century [see references in Davison et al. (2013a), hereafter Part I]. A key aspect of this structure that has not been well established is the temporal and spatial variability of the TMBL, particularly the moisture field. This paper is the third in a series that examines the variability of TMBL properties, particularly water vapor, over the western tropical North Atlantic during the Rain in Cumulus over the Ocean (RICO) experiment (Rauber et al. 2007). In Part I, the complete set of island-launched soundings from RICO was used to investigate the statistical characteristics of the TMBL environment. It was shown that the dominant feature of the TMBL was moisture variability. Very large positive and negative vertical relative humidity (RH) and specific humidity gradients were commonly observed in individual soundings. Large differences in RH statistics were also found between soundings taken on days classified as disturbed or undisturbed based on daily rainfall rates, with moist air extending higher on disturbed days.

In Davison et al. (2013b, hereafter Part II), we demonstrated that persistent rings of enhanced equivalent radar reflectivity factor (hereafter reflectivity) and detectable spectral width (i.e., reduced below noise values) associated with Bragg scattering were observed in cloud-free regions of the TMBL with the National Center for Atmospheric Research (NCAR) S-band 10-cm-wavelength, dual-polarization Doppler radar (S-Pol) during RICO. We further showed that the Bragg scattering layers (BSLs) are persistent, coherent features.
of the TMBL that delineate aspects of its mesoscale structure. We provided evidence that radar BSL boundaries can be used to track the evolution of the RH field, specifically maxima and minima in the vertical RH profile.

In this paper, we examine the statistical behavior and longevity of the BSLs and the layers without coherent radar echo between them (hereafter clear layers), and how these layers are affected by various environmental factors. Based on these results, we reconceptualize the TMBL model and use satellite cloud-top-height retrievals to support our results. Finally, we discuss a possible approach for modeling this environment, in light of the changes in TMBL conceptualization presented in this series of papers.

2. Statistical characterization of the BSLs

a. Methodology

The data used in this analysis come from the S-Pol radar, deployed on Barbuda during RICO between 24 November 2004 and 24 January 2005. In Part II, we introduced a technique based on the Haar wavelet to quantitatively determine the location in range of BSL edges for S-band radars scanning in plan position indicator (PPI) mode. We used this technique to determine the mean BSL boundary locations for individual radar scans, and constructed time–height diagrams of the BSLs (e.g., Figs. 4–6 in Part II). In this paper we consider the spatial and temporal statistical characteristics of the BSLs.

Figure 1 shows an example of the BSLs observed on 29 November 2004. In this figure, the red (blue) dots each denote the top (base) of a BSL for a single radar PPI scan. To determine statistical characteristics, the data points representing BSL boundary locations (e.g., Fig. 1a) had to be remapped to evenly distributed time intervals. Initially, the points associated with each BSL base (top) were identified. The BSL base (top) altitudes were then averaged every 5 min using a 15-min window (Fig. 1b). This provided regularly spaced data (288 bins, each 5 min wide, per day) for the calculation of BSL and clear-layer statistics across all 62 days of the RICO project.

b. Statistical results

1) MEAN STRUCTURE AND DIURNAL CHARACTERISTICS

Following Stevens (2006), the TMBL can be broadly characterized in terms of two layers, a well-mixed subcloud layer (hereafter the “mixed layer”) and a poorly mixed cumulus cloud layer (Betts 1997). Between these layers is a thin layer called the transition layer, which typically contains shallow clouds. On average, 3.5 BSLs were present above the transition layer when all data were analyzed across the RICO period. The overall sample deviation was 1.5 layers, while the maximum number of BSLs detected above the transition layer was 9. Figure 2 shows the average number, the sample deviation $\sigma$, and the maximum number of BSLs as a
function of time of day for the RICO time period. The number of BSLs present appears insensitive to time of day. The median depth of the BSLs was 347 m (see Fig. 3). When the BSL depths were subdivided into day and night categories, the median daytime BSL depth, 357 m, was only slightly larger than that of the nighttime median depth of 340 m. The median depth of the clear layers separating the BSLs was 351 m. No diurnal difference was found in the clear-layer depths (see Fig. 4).

The mean altitude of the mixed-layer top based on the BSL analysis was 400 m. This value was determined using radar reflectivity scans with elevation angles from 1° to less than 2° to avoid near-radar sidelobe contamination caused by a slight ridge on the eastern side of the

**Fig. 2.** Mean number of BSLs as a function of time of day, calculated at 5-min intervals for the entire RICO project (solid blue). This mean excludes the BSL associated with the transition layer. The dashed red lines show ±1σ from the mean values. The solid black line shows the projectwide average. The black dots show the maximum number of BSLs detected for a given time interval, again excluding the transition layer.

**Fig. 3.** Median BSL depths as a function of time of day, calculated at 5-min intervals for the entire RICO project (solid blue). The 30th and 70th percentiles are shown as dashed red lines, and the 10th and 90th percentiles are shown as dashed green lines. The projectwide median is shown by the solid black line at 347 m. Sunrise and sunset are indicated by the solid vertical black lines. The daytime (orange) and nighttime (teal) values of the percentiles are shown as thin solid lines. The range of BSL depths is given by the brown dots.
island. Estimates of the mixed-layer top based on the analyses in Part I (see Fig. 12 in Part I) range from about 300 m for soundings from active days [based on rain rates from Snodgrass et al. (2009)] to about 500 m for soundings during suppressed days.

The mean height of the transition-layer top depended upon the elevation angles used in the analysis. Using elevation angles from 1° to less than 2°, the mean transition-layer top was located at 750 m. Using elevation angles 5° and greater, it was found to be 850 m. There is evidence to suggest that the source of this difference is a combination of the radar geometry (i.e., the different size and extent of the horizontal areas sampled during PPI scans at different elevation angles) and transient meteorological features, particularly shallow clouds, observed with the different geometries. For example, Fig. 5a shows periodic increases in the transition-layer top height measured at the higher elevation angles associated with phenomena with a time scale of about 3–5 h (e.g., at 1000, 1500, 1800, and 2200 UTC; see red dots indicated by red arrows). These do not appear in the lower-elevation-angle results (black dots indicated by black arrows). Individual radar images for the lower elevation angles (e.g., Fig. 5b) show considerably more asymmetry in the height of the (BSL) transition-layer top compared to higher-elevation-angle measurements (Fig. 5c). When estimating the average transition-layer-top altitude, the small-scale variability for the lower-elevation-angle scan is averaged out because of the greater spread in sampling area. We will show evidence in section 4 that these differences may be related to variability in cloud-top heights near the transition-layer top.

The mixed-layer top exhibited an apparent slight diurnal cycle, with the mean daytime mixed layer about 30 m thicker than the mean nocturnal mixed layer (e.g., see red and blue lines in Fig. 6b). In contrast, the top of the transition layer exhibited no diurnal cycle (Fig. 6a). The mean transition layer was thickest (404 m) at 0720 UTC (0320 LST) and thinnest (312 m) at 1940 UTC (1540 LST). The reduction in the depth of the transition layer following sunrise should contribute to dissipation of shallower clouds. This trend in shallow cloud cover was indeed consistent with our visual observations of rapid clearing of the shallow clouds on most mornings during RICO.

2) LIFETIME OVER THE RADAR

Because the radar data were not always continuous, the BSLs were classified into three groups: 1) BSLs whose entire lifetimes over the radar \( t \) were captured; 2) BSLs with at least a 1-h gap in radar data at one end point, reducing \( t \); and 3) BSLs with at least 1-h gaps in radar data cutting off both ends, again reducing \( t \). The value of \( t \) for the second and third categories will be biased low because of radar down times. Gaps in data of less than 1 h were ignored, as BSLs could be unambiguously paired across such small data gaps. Data segments shorter than 4 h because of radar gaps on both sides were excluded from this analysis.

Although generally perceived as layers, the BSLs can also be branching in nature. Sometimes a BSL will split into two layers; sometimes two layers will merge into a single layer. Some BSLs experience both divisions and mergers within their lifetimes (e.g., 0000–0700 UTC in Fig. 5 of Part II). For these reasons, a BSL with all its branches was counted only once, and \( \tau \) was determined as the time interval between the time the BSL was first identified and the time its last branch disappeared (or
was cut off). Using these criteria, 359 BSLs were observed with the radar across the RICO project.

Figure 7a shows cumulative frequency diagrams of $t$ for different branching structures. The black line shows the overall statistics for $t$. The median value of $t$ was 8.4 h. Roughly 25% of the BSLs had $t > 20$ h and about 10% had $t > 31$ h. The maximum value of $t$, 86.7 h, was shortened on either side by data cutoffs. The remaining lines in Fig. 7a show $t$ as a function of branching characteristics. Of the 359 BSLs observed, 81% exhibited no branching, 5% exhibited mergers only, 6% exhibited divisions only, and 8% experienced both mergers and divisions. Approximately a third of the BSLs with no branching had $t$ on the order of 5 h or less, a third had $t$ between 5 and 10 h, and the remaining third had $t$ between 10 and 64 h. BSLs that exhibited branching tended to be observed longer than those that did not, and longest for those that exhibited both mergers and divisions.

Figures 7b–d show the data subcategorized based on the number of data cutoffs. Comparing Figs. 7b–d, the bias in $t$ introduced by data cutoffs was particularly evident for the BSLs that exhibited both mergers and divisions. The median value of $t$ for BSLs exhibiting mergers and divisions decreased by about 7 h when one data cutoff occurred and about 7 additional hours when two data cutoffs occurred. The effect of the cutoff bias was less obvious for BSLs that did not branch.
Composited sounding profiles used in past studies would suggest that only two or three BSLs would be detectable by radar, specifically those associated with the transition layer, the TMBL top/tropical inversion, and near the 0°C isotherm when a stable layer is present. Because the current conceptual model of the TMBL allows for only two BSLs, it becomes a point of interest to find out the relative lifetimes over the radar of BSLs given their relative vertical positions. For instance, are the middle layers (which are not expected to exist based on the current TMBL conceptual model) the ones that are short lived? It is possible for a BSL to occupy more than one position for two reasons: 1) because of their branching structure (as mentioned above) and 2) because a shorter-lived BSL showing up (or disappearing) above or below a given BSL will change the given BSL’s relative vertical position. Thus, BSLs were grouped into six categories by relative vertical position: 1) bottom, 2) bottom and middle, 3) middle, 4) middle and top, 5) top, and 6) bottom, middle, and top. Here, “bottom” refers to the transition layer and “top” refers to the topmost BSL observed at a given time.

As can be seen in Fig. 8a, layers exhibiting a range of \( \tau \) values occurred in all position categories. All categories except the top had at least one BSL last in excess of 48 h. The topmost BSLs had the smallest values of \( \tau \), most likely because of dissipation of vertical moisture gradients as dry air from aloft mixed with boundary layer air across the top of the TMBL. Possible alternative explanations could be that higher layers develop from smaller radio refractivity gradients (because of colder temperatures reducing the possible range of radio refractivity.

![Mean Transition Layer Statistics](image-url)
values) or that the layers are harder to detect being at further range (reduced radar sensitivity), making them harder to track continuously over long time periods.

The middle and bottom BSLs had progressively larger values of $t$. Layers occupying more than one vertical position category had significantly larger $t$. There were only four BSLs whose branching structure ranged from bottom to top. The shortest of these was present in excess of 42 h. Figures 8b–d showed the effect of data cutoffs on the $t$ distributions. The impact of data cutoffs on $t$ estimates are most notable in Fig. 8d, where the cumulative frequency distributions appear to converge.

3) POTENTIAL SOURCES OF BSLS

A fundamental question concerning the BSLs is whether they exist as layers over large regions of the Atlantic and are simply transported by the wind over the radar or are continuously generated and altered by cloud and turbulence processes. A way to address this question is to calculate back trajectories of air parcels beginning from the radar location at the altitudes and time of the first appearance of long-lived BSLs, such as those appearing in Fig. 9a. If the BSLs are simply transported over the radar with no vertical motion ($w = 0$), then their heights, moving forward in time, should approximate the altitudes of the trajectories moving backward in time. To calculate back trajectories, we used National Centers for Environmental Prediction (NCEP)–NCAR global reanalysis data with the National Oceanic and Atmospheric Administration (NOAA) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess 1998, 2010).

Figure 9b shows back trajectories launched at 1400 UTC 1 January 2005 beginning at the radar site from a series of altitudes spanning the depth of the TMBL. These trajectories are characteristic of many other days that we examined during RICO and follow expectations based on common understanding of the general circulation features of the tropical Atlantic. Specifically, the trajectories imply that air arriving in the upper layers of the TMBL originated several kilometers higher in the free troposphere, while air parcels arriving in the lower layers of the TMBL first ascended over the northern subtropical Atlantic and then descended slightly as they entered tropical latitudes. If the BSLs were simply transported over long distances, then these trajectories imply that the moisture that characterizes the BSL bases would have sources above the TMBL and near the ocean surface, the former of which is improbable. A more physical interpretation, although it must be considered speculative with the data we have available, is that cloud detrainment of moisture, which occurs continually within the trade wind cloud layer, is concentrated in layers that possess marginally greater static stability. This is consistent with...
the occurrence of moisture layers commonly observed on soundings.

4) Relationship of BSLs to Rain Rate and Surface Meteorological Variables

BSL and clear-layer depths were examined as a function of daily rain rate from RICO using the data presented in Snodgrass et al. (2009) (see Fig. 10). Figures 11 and 12 show the median depths of the BSLs and the clear layers observed on days with precipitation rates ranked as in Fig. 10. Layers on the rainiest days were generally about 100 m thicker than layers on the least rainy days. However, the number of layers present did not appear to have any relationship to rain rate. Together, these two observations imply that the TMBL was typically thicker on rainier days. This is consistent with the sounding analyses in Part I, which showed moisture extending to higher altitudes on rainier days.

Surface air temperature, wind speed, and wind direction were determined using data from the NCAR portable automated mesonet (PAM) station located at the sounding launch site, Spanish Point, Barbuda (see Fig. 2 in Part II). These data were recorded at 5-min intervals that could be directly linked to the time intervals used for the moving window averages. Surface wind direction was the only variable that appeared to have a relationship to the number of BSLs observed (see Fig. 13). Averaged over the RICO project, the fewest number of BSLs were present when surface winds were northerly. The number of BSLs trended upward for surface winds with an increasingly easterly component and even more so for winds with a southerly component. This trend in behavior is consistent with the sounding analyses in Part I and the conceptual model of a deepening of the TMBL toward the equator. Simply, more BSLs fit within a deeper TMBL. Surface wind direction had no apparent relationship to the depth of the BSLs or clear layers. There was also no apparent relationship between the number/depth of BSLs or clear layers and surface wind speed or temperature.

3. Confirmation of RH layering implied by BSLs using independent data

The picture portrayed by S-band radar of the typical tropical trade wind profile during RICO consists of the following: 1) a mixed layer capped by a transition layer, with the transition layer appearing as an echo layer produced by a combination of Rayleigh scattering from shallow clouds and Bragg scattering; 2) three to four BSLs above the transition layer, each separated by clear layers, with each layer (Bragg or clear) about 350 m thick; and 3) the free atmosphere above the highest BSL. The tops of the BSLs are collocated with local RH minima.

FIG. 8. Cumulative frequency of occurrence of BSL lifetimes over the radar subdivided by relative location for (a) all BSLs, (b) BSLs with no gaps in sampling, (c) BSLs with one end terminated by a data gap, and (d) BSLs with both ends terminated by data gaps. The number of BSLs in each category is displayed on the plots.
and the bases with local RH maxima, indicating a persistent layered structure for the typical moisture profile.

Two sets of independent observations can be used to support this structure, specifically, satellite cloud-top-height retrievals derived from data taken by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument on the Terra satellite platform (Zhao and Di Girolamo 2007) and a 915-MHz wind profiler signal-to-noise ratio (SNR) from the research vessel (R/V) Seward Johnson, which traversed the waters northeast of Barbuda during the latter half of RICO (Zuidema et al. 2012). We start with the expectation, confirmed with the available sounding data in Part II, that RH maxima are collocated with BSL bases.

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**Fig. 9.** (a) Montage of 3.5 days of radar BSL data plotted with earliest time (1400 UTC 1 Jan 2005) on the right. (b) HYSPLIT model back trajectories starting at the radar at 1400 UTC 1 Jan 2005.

**Fig. 10.** Daily area-averaged rainfall rate (mm day$^{-1}$) sorted from rainiest to least rainy day and corresponding cumulative frequency distribution (from Snodgrass et al. 2009).
and RH minima are collocated with BSL tops. Clouds rising through the trade wind layer will preferentially detrain moisture near the base of stable layers when such layers exist. Over time, an ensemble of clouds will moisten a layer below the base of the stable layer such that an RH maximum will occur somewhere below the base of the stable layer and an RH minimum will occur above the base of the stable layer. In addition, the cloud tops, particularly stratiform remnants outside the cumulus cores, will generally be coincident with the base of stable layers. It is reasonable to expect that RH maxima should occur at the preferred heights of maximum cloudy-air detrainment and RH minima will occur at heights with little or no cloudy-air detrainment. We therefore anticipate that the RH minima associated with BSL tops will occur near but just above (locally) preferred cloud-top heights. To verify this idea, we compared BSL-top altitudes with cloud-top-height retrievals from the satellite study of Zhao and Di Girolamo (2007).

Zhao and Di Girolamo (2007) examined cloud-top height as a function of cloud diameter using ASTER data. The data were taken over the western tropical Atlantic from September to December 2004. They used

![Image](image_url)

**Fig. 11.** Median BSL depth for each day (solid blue curve), with trend line (solid blue straight line). The days are arranged as a function of rain rate according to Fig. 10. The trend-line equation is shown in the blue box. Percentiles are shown as in Fig. 3. Also shown is the projectwide median depth of 347 m (dotted line).

![Image](image_url)

**Fig. 12.** As in Fig. 11, but for the clear layers between the BSLs.
a 90-m cloud mask that was further verified to be completely cloudy at 15-m resolution for all of the clouds in their study. The data they used were all taken around 1030 LST because of the sun-synchronous orbit of Terra. Figure 14 shows their cloud-top height distribution, binned every 100 m, for cloudy pixels associated with clouds within a given size range (based upon cloud diameter), and normalized by the total number of cloudy pixels analyzed.

Figure 14 supports our description of the transition layer as a layer of shallow clouds. In the figure, the preferred cloud-top height altitude is 750 m for clouds with diameters less than 4.5 km, closely matching the transition-layer top from the BSL analysis at the lower elevation angles. When clouds of all diameters were included in the satellite analysis, the preferred cloud-top-height altitude increased to 850 m, consistent with the BSL analysis of the transition-layer top at higher elevation angles. The elevations of the next four maxima in cloud-top heights for all clouds in the satellite analysis were found at 1550, 2050, 2750, and 3400 m (this last elevation was rounded to 3400 m because the individual curves varied between 3350 and 3450 m). Thus, the peaks in cloud-top-height frequency were separated vertically by 663 m, very close to the roughly 700-m median depth between the tops of two vertically adjacent BSLs.

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**FIG. 13.** Mean number of BSLs (solid blue line, scale on left) ±1σ (dashed red lines) as a function of surface wind direction, and number of 5-min samples as a function of surface wind direction (histogram, scale on right).

**FIG. 14.** Cloud-top-height distribution as a function of cloud diameter for 90-m-resolution cloud-filled pixels from ASTER data (from Zhao and Di Girolamo 2007).
We next compared the frequency of occurrence of BSL tops (e.g., see red dots corresponding to RH minima in Fig. 5a) versus altitude for the entire RICO dataset with the log of the satellite-derived cloud-top-height frequency versus altitude (see Fig. 15). Peaks in the frequency diagrams for both curves occur at many of the same altitudes, suggesting strongly that there exists a relationship between cloud tops and BSL tops. The correlation coefficient between these two curves was 0.92. These data support the idea that the RH minima associated with the BSL tops correspond to preferred cloud-top heights within the TMBL. The median depth of the BSLs suggests that RH maxima occur in the preferred cloud detrainment region about 350 m below cloud top.

The relationship between clouds and BSLs can be further understood by examining the 915-MHz wind profiler SNR time series (Fig. 16). As noted by Zuidema et al. (2012), the layered SNR values near 0 dB at higher altitudes were associated with Bragg scattering caused by humidity gradients affecting the clear-air index of refraction. In this figure, clouds, precipitation, and BSLs were present. Note that the cloud-top heights are generally coincident with BSL tops, and that the clouds are not necessarily topping out at the highest-altitude BSL.

The variability and layering in the cloud-top heights indicated by the satellite data and the variability and layering in the RH field, as indicated by the location and number of BSL tops, strongly imply that the “mean state” of the trade wind layer characteristic of composited soundings used for many simulations rarely, if ever, exists over the tropical North Atlantic. However, the fact that there are preferred altitudes to both the BSLs and the cloud-top heights indicate that there is some preferred structure to the variability.

We do not have sufficient data to quantitatively analyze the specific feedback relationships between cloud detrainment, turbulence, radiative processes, and large-scale forcing in the formation and maintenance of moisture layering indicated by the long-lived BSLs. It is clear from the satellite–BSL comparison, however, that the internal stability structure of the TMBL is influencing, and is influenced by, cloud detrainment. Future research should be targeted at understanding these relationships.

4. A revised conceptual model of the TMBL

Campaigns carried out in the trade wind regime have characterized the mean state of the TMBL based on radiosonde, dropsonde, and aircraft flight-level data. Averaged or composited profiles from these campaigns have been used to create a series of thermodynamic and moisture profiles that have served as the initial state for
the vast majority of large-eddy simulations (LESs) and column model simulations of the western Atlantic trade wind environment [e.g., Puerto Rico experiment (Sommeria and LeMone 1978), phase 1 of the Barbados Oceanographic and Meteorological Experiment (BOMEX) (Stevens et al. 2001), phase 3 of BOMEX (Siebesma et al. 2003), and RICO (VanZanten et al. 2011)]. Each representative profile used in these modeling studies was generated by averaging soundings or aircraft flight legs from a subset of the experimental days during which the environment was characterized as “undisturbed” or “suppressed.” The Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) RICO profile of RH, for example, appears on the right side in Fig. 17.

The current conceptual model of the TMBL is largely based on the mean state of the undisturbed environment, with little explicit mention of its inherent moisture variability. This conceptual model consists of a subcloud mixed layer demarcated by the mixed-layer top, a transition layer often containing very shallow clouds, and a deeper, poorly mixed cloud layer extending to the tropospheric inversion (e.g., Betts 1997).

The analyses presented in Parts I and II and this paper, together, imply that above the transition layer, high levels of moisture variability are common. Nevertheless,
analyses of radar data reveal a clearly defined structure to the variability not easily ascertainable from soundings. Figure 17 summarizes the implied characteristics of the RH field within the TMBL, as inferred from the BSL analyses. Above the transition layer, the TMBL typically contains three to four persistent, stacked moist and dry layers, which, when viewed from a fixed location, can persist for a few hours to more than a day. The mechanisms by which these humidity layers form and are maintained are likely associated with the action of turbulent mixing in a shallow layer, creating stable layers above and below that favor cloud detrainment. The top of the TMBL can vary in altitude over a time scale of hours as humidity gradients develop and dissipate through the action of mixing between the relatively moist air of the TMBL and the subsiding dry air aloft. Moreover, the TMBL top often can become poorly defined as shorter-lived (on the order of hours) moist layers appear above a preexisting, longer-lived moist layer, which, from a sounding point of view, would more likely be identified with the TMBL top.

Highly variable tropical moisture profiles are not limited to the RICO campaign. The studies focusing on the mean undisturbed state stand in sharp contrast to the numerous studies looking at exceptions to the “expected” moisture profile (such as that shown in Fig. 17). Examples include papers describing mixing ratio (\( q \)) reversals and double \( q \) reversals (e.g., Betts and Albrecht 1987; Kloesel and Albrecht 1989), multiple inversions (e.g., Cao et al. 2007), (multiple) humidity drops (e.g., Mapes and Zuidema 1996), and large variations in specific humidity profiles and the mixed-layer top measured over short time and space scales (Barnes et al. 1980). Given the radar portrayal (as shown in Fig. 17), satellite cloud-top height statistics, and wind profiler data, we believe that these “exceptions” may not really be exceptions but may, in fact, be the rule—something that was repeatedly observed but where observers lacked sufficient information to make a definitive statement about the prevailing nature of such exceptions in the trade wind regime.

5. Summary and conclusions

a. Conclusions from this paper

This paper is the third in a series that explores moisture variability in the tropical marine boundary layer (TMBL). In this paper, we further investigated Bragg scattering layers (BSLs) and their relationship to the vertical distribution of relative humidity (RH) and TMBL structure. In Part II, we showed that BSLs are a common feature of cloud-free regions of the western North Atlantic TMBL. We provided evidence that the radar BSLs exist in layers with tops defined by local RH minima and bases defined by local RH maxima. In this paper, we examined the statistical behavior and longevity of the BSLs and the clear layers between them. Based on these results, we presented a revised conceptual model of the TMBL that is characterized by significant moisture variability and a larger vertical extent than before. Furthermore, we provided evidence based on satellite and wind profiler measurements that the layered RH structure is related, at least in part, to the cloud structure within the TMBL.

The key findings related to BSL structure and longevity as well as environmental influences on the BSLs are as follows:

1) On average four to five BSLs were present at any given time, including the BSL associated with the transition layer.
2) BSLs and their clear-layer counterparts each had a median thickness of about 350 m.
3) BSLs had a median lifetime over the radar of 8.4 h, with about 25% having lifetimes over the radar in excess of 20 h.
4) The number of BSLs was largest at times when surface winds had the most southerly component and smallest at times when the winds were most northerly, with no significant difference in depth.
5) Both BSLs and clear layers increased in depth with increasing rain rates, with the rainiest days producing layers that were about 100 m thicker than the driest days.

The implications of these statistics on our understanding of the TMBL are as follows:

1) The mean RH field in the TMBL exhibits layering on large spatial scales (greater than our analysis domain for the radar, approximately 90-km-diameter circle), although local variations in the vertical structure of RH are common because of the proximity of detraining cloudy air (see Part II).
2) The layering of the RH field results, at least in part, from detrainment of clouds at preferred elevations within the TMBL. Support for this conclusion was based on the relationship between the satellite-determined cloud-top-height frequency and the frequency of occurrence of BSL tops, as well as the wind profiler data.
3) The mean depth of the transition layer was 350 m, but it exhibited a diurnal cycle whose mean ranged from 334 m in the daytime to 363 m at night. This diurnal cycle was associated with variations in the depth of the mixed layer, which was deeper during daytime.
The mean transition-layer top exhibited no discernible diurnal variability. The daytime thinning of the transition layer was in keeping with in-field empirical observations of shallow-cloud dissipation following sunrise.

**b. Summary of the paper series**

This series of papers demonstrates that the moisture field of the TMBL is highly variable, both spatially and temporally. The dominant feature of the TMBL is the moisture variability. Comparison of dropsondes released during RICO in sets of approximately six revealed humidity differences of up to 70% RH (8 g kg\(^{-1}\)) measured at the same altitudes within 25 min and 60 km (see Fig. 17 in Part II). TMBL-top heights derived from dropsondes could vary by 1.5 km or more within a single set of near-coincident dropsondes.

Figure 18, which shows RH from a set of six dropsondes (see Part II) and associated Bragg scattering layers, can be used to synthesize the results of these three works. In this figure, the top of the TMBL, based on the humidity structure in the numbered panels, could be interpreted at either 3400 (A), 2400 (B), or 1800 m (C). The radar BSL analysis for the same time reveals a layered structure in the moisture field associated with each of these altitudes. Time–height diagrams of the BSL structure provide robust depictions of the framework of this environment, which, when paired with soundings, jointly reveal a complex but definitive characterization of the highly variable nature of moisture in the trade wind layer.

Individual or averaged moisture profiles are not realistically capable of representing the moisture profile for this environment. The average provides a poor representation because moisture variability is too high. Given this variability, the question arises as to what an appropriate approach would be for modeling this environment to develop representative parameterizations for global climate models. A possible solution is to use an ensemble approach where simulations would be initialized with a range of conditions characteristic of the inherent moisture variability and its layered structure. The results of these simulations would better characterize the variability and establish the inherent robustness of any parameterizations that might be developed.

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