Using Multiple Instruments to Better Understand Wind Profiler Observations of the Stratocumulus-Topped Marine Boundary Layer

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Introduction

Clouds affect Earth's energy budget as they reflect, absorb, and reradiate radiation from above and below. Of particular interest are marine stratocumulus (Sc) clouds because of their extensive and persistent coverage near western coasts of continents. The extensive marine stratus deck in the southeast Pacific Ocean (Figure 1) plays a critical role in the dynamics of the ocean-atmosphere system as well as the global atmospheric circulation in the eastern Pacific (Raymond et al., 1999). The tops of marine Sc are, to a first approximation, coincident with the top of the marine boundary layer (MBL). Both the height of the MBL and the thickness of the Sc vary in space and time, and these variations affect both vertical mixing between the ocean and the atmosphere as well as radiative processes within the atmosphere. Unfortunately both the height and thickness of the Sc are poorly measured by satellites. It has been suggested that cloud depths could be calculated using data from a combination of radar wind profilers and ceilometers. (Wind profilers could determine the height of the MBL, assumed to coincide with Sc tops, while ceilometers could measure cloud base heights.)

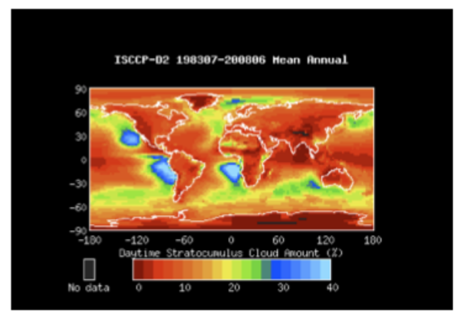

Figure 1. Global mean stratocumulus cover between July 1983 and June 2008. Image provided by ISCCP, NASA, from their website at http://www.isccp.giss.noaa.gov.

Data

The data used in this research was collected during cruises conducted as part of the Pan American Climate Study (PACS). Wind profiling radars, ceilometers, and radiosondes, along with other instruments, were deployed on the R/Vs Ronald H. Brown (Fall) and Ka'imi Moana (Spring) cruises in the east Pacific Ocean. Stratocumulus are more extensive during boreal fall than during spring in the southeast Pacific, so data from two fall cruises were used for this study: Fall 2000 (October 27 - November 12) and Fall 2004 (October 29 - November 27). The ship tracks are shown in Figures 2 and 3. The blue shading indicates the amount of average Sc cloud coverage for the indicated month, as retrieved from the International Satellite Cloud Climatology Project (ISCCP). Dark blues represent high coverage while light blues represent low coverage.

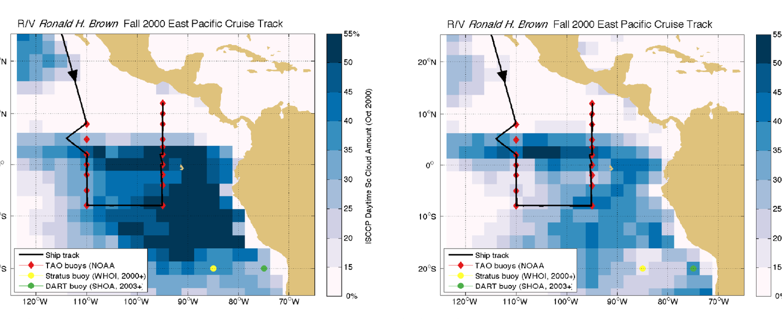

Figure 2. Track of the R/V *Ronald H. Brown* during the Fall 2000 cruise. Shading indicates the monthly average Sc amount during October 2000 (left) and November 2000 (right).

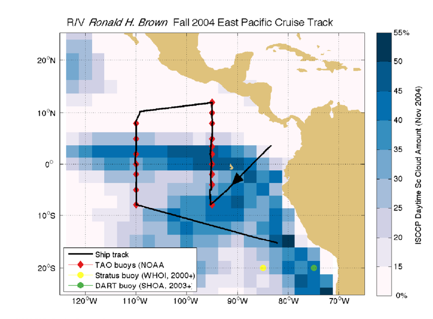

Figure 3. Track of the R/V *Ronald H. Brown* during the Fall 2004 cruise. Shading indicates the monthly average Sc amount during November 2004.

Wind profilers are dwelling (not scanning) radars and measure signal-to-noise ratio (SNR), radial velocity, and spectral width. Figure 4 shows reflectivity (SNR multiplied by the range squared), vertical velocity, and spectral width from the profiler's vertical beam on November 1, 2000. The plotting software auto-scaled these "raw" data, showing atmospheric as well as non-atmospheric data. SNRs and spectral widths, in particular, are unrealistically large; atmospheric-induced SNRs should not be larger than 30dB and spectral widths should not be as large as 6 m/s.

Three methods were used to refine the data. A minimum threshold of detectability (Riddle et al., 2012) was used to clean out non-atmospheric data with very low SNRs, leaving mostly atmospheric signal. With the data from 2000, subtracting 1.5dB from Riddle's threshold resulted in a beneficial tradeoff of a lot more "good" data points for a gain of a few "bad" data points. Therefore, for both cruises, when SNR was less than the Riddle Threshold (minus 1.5 dB in 2000) all three variables were set to NaN. In addition, all variables were excluded if associated SNRs were above 30dB. Finally, if spectral width was larger than 3 m/s, both spectral width and signal-to-noise ratio were set to NaN. The resulting "thresholded" data for November 1, 2000 are shown in Figure 5.

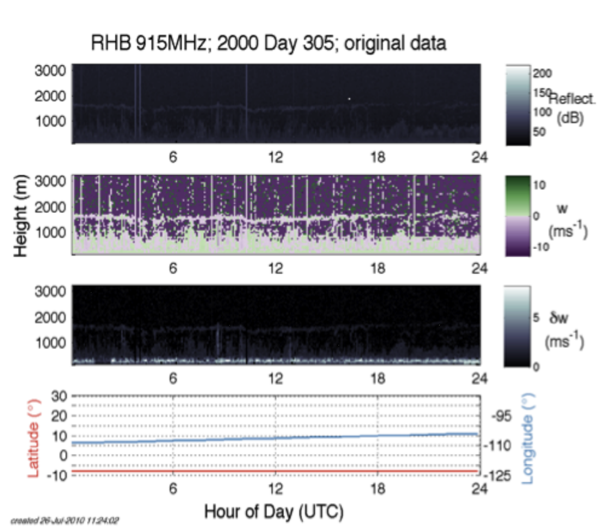

Figure 4. "Raw" profiler data from November 1, 2000: the vertical beam's reflectivity, vertical velocity, and spectral width as functions of time and height, together with ship position.

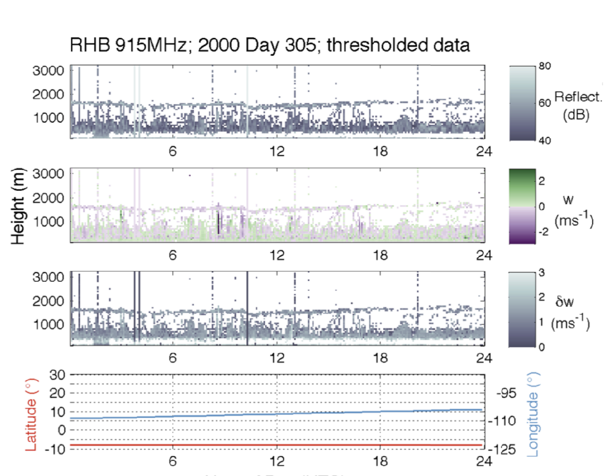

Figure 5. "Thresholded" profiler data from November 1, 2000: the vertical beam's reflectivity, vertical velocity, and spectral width as functions of time and height, plus ship position.

First Approach

Our first approach used data from the Fall 2000 cruise. It relied on only one instrument, the 915-MHz profiler, and on fuzzy logic. This approach generated additional questions without answering the original one!

The Bianco et al. (2008) boundary layer (BL) height algorithm takes hourly profiles of reflectivity, velocity variance, and spectral width from the profiler's vertical beam to estimate the height of the convective BL over land. Here, the algorithm was tested in a marine BL region and on a moving platform, using data that had been "cleaned" as described in the previous section. Minor modifications were made to the algorithm for this purpose, e.g. the algorithm was allowed to run 24 hours a day instead of during the daytime only, and the usual confidence constraints were loosened. Figure 6 shows a representative example of the results, plotted on top of the profiler reflectivity, vertical velocity, and spectral width. The estimated heights closer to the ground are probably wrong; the estimated heights near 1000m could conceivably be correct.

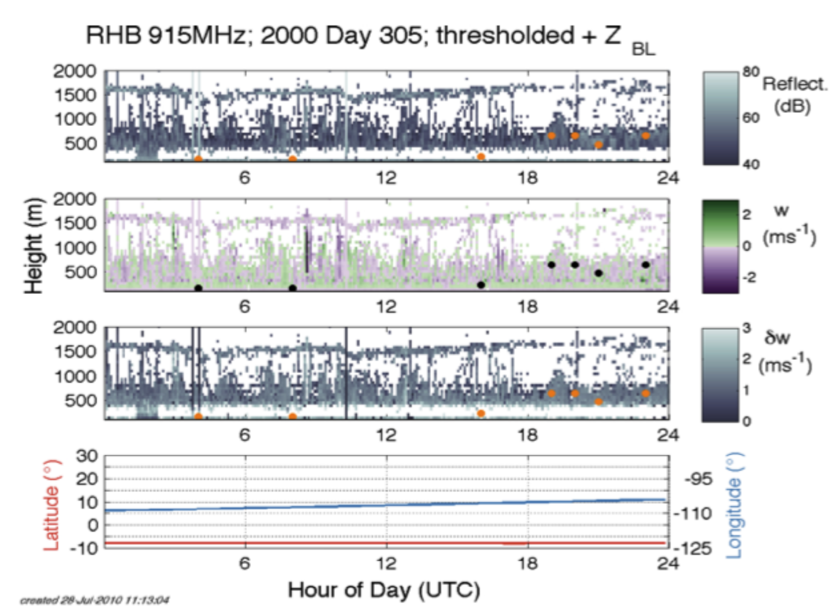

Figure 6. "Thresholded" profiler data from November 1, 2000 (reflectivity, vertical velocity, and spectral width) as functions of time and height. Colored dots indicate BL heights estimated hourly with a modified version of the Bianco et al. (2008) algorithm.

Many days exhibited the thin layer of enhanced reflectivity between 1000m and 2000m seen in Figure 6. The Bianco algorithm often didn't pick this as the BL top. Below this layer of enhanced reflectivity there was often a region without valid atmospheric returns. We were left with new questions. What is that layer of enhanced reflectivity -- the top of the Sc layer, or the bottom, or something else? Why are there so frequently no atmospheric returns below it?

Second Approach

Our second approach used data from the Fall 2004 cruise. We used more instruments and no automation, focussing on 14 days during which the ship was in a region with fairly high monthly average Sc (c.f. Figure 3) and during which the profiler reflectivity exhibited the thin layer of enhanced reflectivity noted during the Fall 2000 cruise. This approach has given us some preliminary answers while revealing at least one additional pitfall.

Figure 7 shows reflectivity, vertical velocity, and spectral width on November 3, 2004. Also displayed is a graph of ship position through the day; this day is unusual in that the ship was on station rather than cruising. The median cloud base height, as determined by the ceilometer, is overplotted with orange or black dots. On this and the other 13 days studied, the measured cloud bases were usually below (and very occasionally in) the thin elevated layer of enhanced reflectivity. Thus, we believe the layer is not the bottom of the Sc deck.

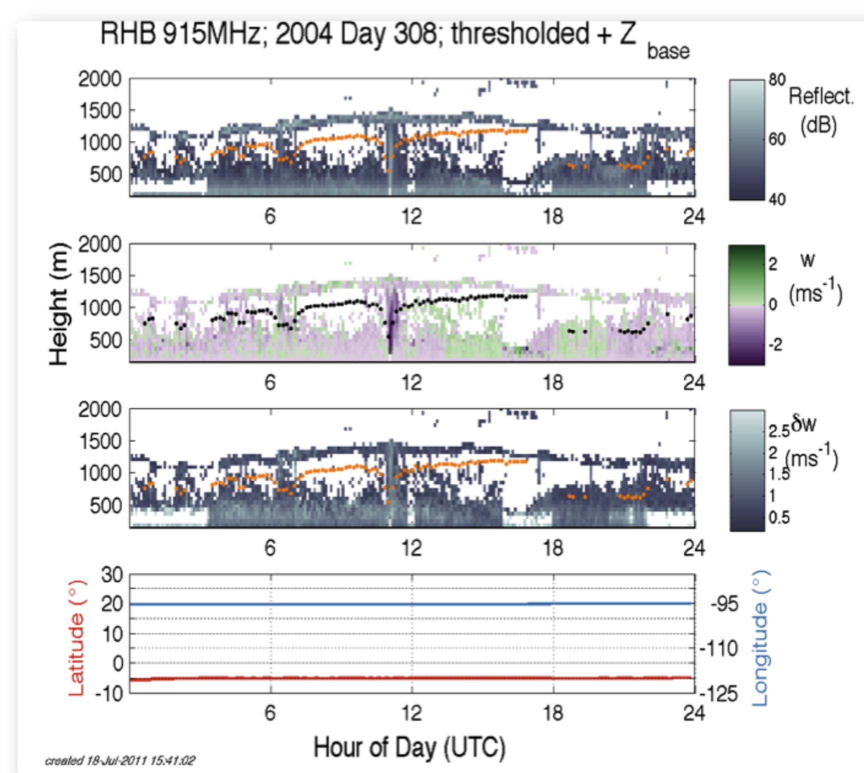

Figure 7. Thresholded profiler reflectivity, vertical velocity, and spectral width from November 3, 2004, overplotted with ceilometer cloud base heights (black or orange dots)..

Profiler reflectivity, ceilometer cloud base, and profiles of relative humidity from radiosondes are compared in Figure 8, again for November 3, 2004. The horizontal orange lines in the humidity profiles represent the ceilometer cloud base heights and the gray dashed lines indicate the reflectivity layer's height during the collection of the lower 3km of the sounding. (There are multiple cloud base and layer heights because the radiosonde takes about 15 minutes to reach 3000m, so all ceilometer and profiler observations within that window are plotted). All four relative humidity profiles show a sharp gradient just above values that are near 100%. The high relative humidities indicate probable Sc and the sharp gradient marks the inversion at the top of the MBL.

The relative humidity soundings are shown again in Figure 9, but now with the top and bottom of the inversion marked by red dots. The structure of the MBL is clearly shown where the bases of the clouds are either below or just at the inversion bottom. The layer detected by the profiler is in the middle of the inversion, though at 17 and 23 UTC that it was almost at the same height as the inversion top but never above it.

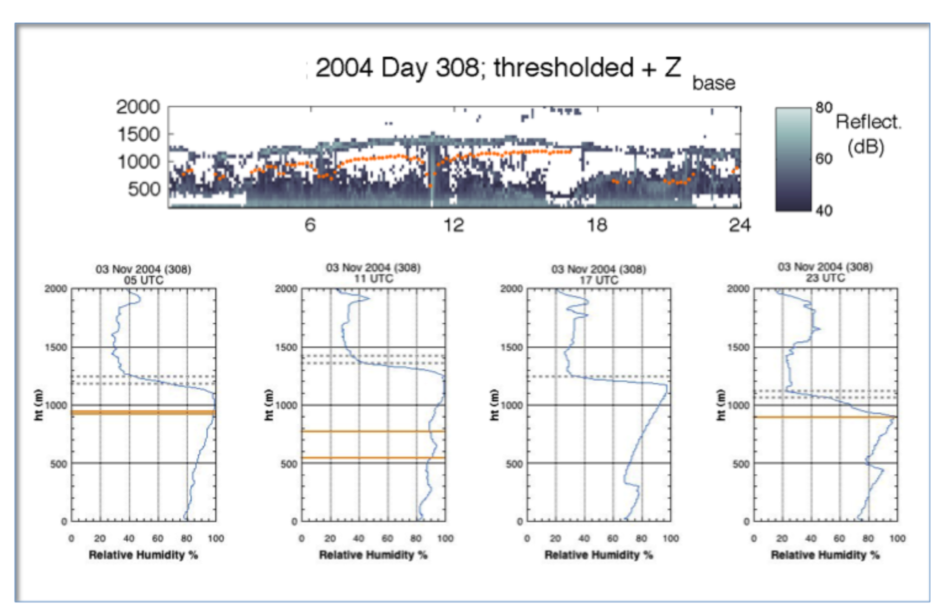

Figure 8. Thresholded profiler reflectivity for November 3, 2004, together with the corresponding humidity soundings. The horizontal orange lines in the soundings represent the ceilometer cloud bases and the dashed gray line represents the height of the layer during the time it took the radiosonde to ascend to about 3km.

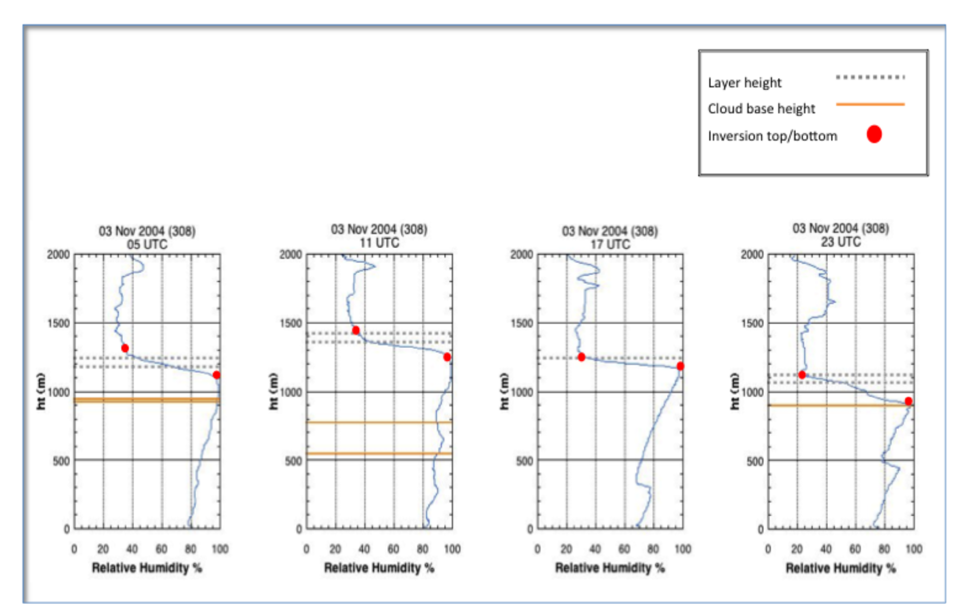

Figure 9. Relative humidity soundings from November 3, 2004; the top and bottom of the inversion are marked with red dots. The horizontal orange lines represent the ceilometer cloud bases and the dashed gray line represents the height of the layer of enhanced profiler reflectivity.

Resolved and Unresolved Issues

The goal of this study was to identify the tops of marine Sc using data from a subset of instruments deployed during research cruises in the southeast Pacific. Our first approach, which relied on one instrument and fuzzy logic, generated additional questions without clearly answering the original one. Our second approach, which used more instruments and far less automation, gave us some initial answers. However, it also revealed at least one additional pitfall for those who would like to automate the detection of the MBL top in this region.

Figure 10 highlights part of the November 3, 2004 case study, revealing an additional feature. In the 11 to 23 UTC soundings, a second inversion is clearly seen to develop. The MBL is very moist at 11 UTC; the profiler reflectivity and vertical velocity show precipitation before 12 UTC. At 17 UTC the MBL is drier but a second lower inversion shows up. This appears to be an internal boundary layer; probably a decoupling of the MBL occurred or a new shallow convective BL developed. Features like this could make it harder to develop an MBL detection algorithm.

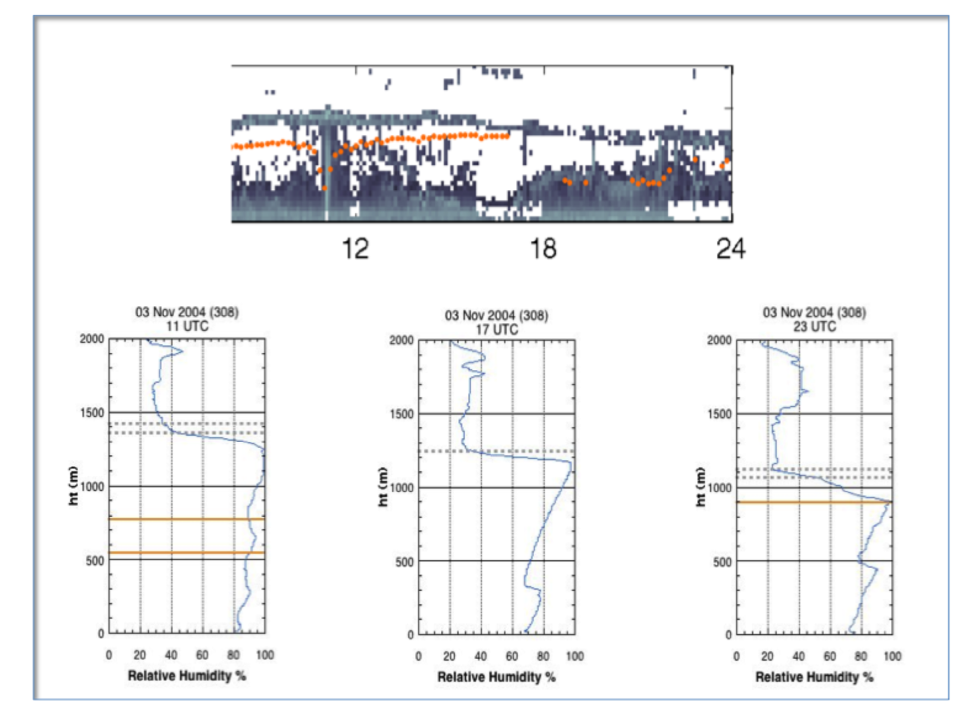

Figure 10. Closeup of data from November 3, 2004, showing a secondary inversion. At 11 UTC, an inversion is apparent at around 300m; it rises to 400m by 23 UTC.

The enhanced reflectivity layer above the gap in the profiler data does seem to be the top of the Sc-topped MBL. Further case studies are underway to confirm this. There are some days in which multiple thin layers are seen; the nature of these is as yet undetermined. Automated determination of the stratocumulus-topped MBL may be complicated by either multiple thin layers of enhanced reflectivity aloft or by the occasional development of internal BLs. The reasons for the mid-BL gap in profiler data remain uncertain at this time, but this gap may also complicate automation. However, we remain hopeful that further case studies using the multiple instrument sets carried aboard numerous southeast Pacific cruises will enable us to confidently use primarily profiler data to identify the top of the Sc layer in this region.

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