

Estimating the Height of the Stratocumulus-Topped Marine Boundary Layer Using Wind Profilers

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ABSTRACT

Stratocumulus clouds frequently form over the cold water of the southeastern Pacific Ocean (SEP). Large in area, they affect the Earth's energy budget by blocking and reflecting solar radiation. In this region of atmospheric stability, the height of the boundary layer is at about the same elevation as the top of the stratus deck. In the fall of 2000, a 915-MHz wind profiler was mounted on the R/V *Ronald H. Brown* to obtain information about the depth of the stratocumulus-topped marine boundary layer at different times and locations. With the tandem of cloud-top heights and ceilometer data (heights of the cloud bases), cloud depth can be determined in order to draw further conclusions on the Earth's radiation budget; however, estimating the height of the stratocumulus-topped marine boundary layer was the scope for this research. Data from daily height-vs-time plots of relevant profiler variables (reflectivity, vertical velocity, and spectral width) for different locations during the cruise in the SEP—near the equator, near the ITCZ, and in the stratocumulus region—were examined. The plots showed data that did not seem to be atmospheric, so a procedure to clean up non-atmospheric data was implemented. The adjusted data were then inserted into a modified version of the Bianco et al. (2008) boundary layer height algorithm. Estimated heights for the marine boundary layer appeared to vary between the surface of the Earth and 1500m. The detected heights will need further verification before they can definitively be considered the height of the stratocumulus-topped marine boundary layer.

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1. Introduction

The boundary layer (BL) is defined as the part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings (Stull, 1988). In the southeast Pacific Ocean (SEP), the marine BL overlaying the cold waters has a height that is about the height of the top of the stratocumulus cloud deck. The shifting depth of this marine BL affects vertical mixing between the ocean and the atmosphere as well as basic meteorology in the lower atmosphere.

The extensive marine stratus deck in the SEP (seen in 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). Cloud depths affect the radiation budget by blocking and reflecting solar radiation that would otherwise be absorbed by the ocean. The sea surface has a mean albedo of 0.05 (Fairall et al., 1996), while stratocumulus clouds reflect between fifty and sixty percent of solar radiation (Stephens et al., 1984). Therefore, when no clouds are present, a maximum amount of solar radiation is absorbed by the water. In contrast, when a thick layer of stratocumulus clouds are present, as much as sixty percent of the radiation is reflected by the clouds, still leaving ninety-five percent of what is scattered towards the surface to be absorbed by the water. In short, deep clouds block shortwave solar radiation by absorption and reflection, whereas shallow clouds allow more radiation to reach the surface. Cloud depths can be calculated using data from radar wind profilers and ceilometers. (Wind profilers can determine approximate heights of the marine BL as well as stratocumulus tops while ceilometers measure cloud base heights.)

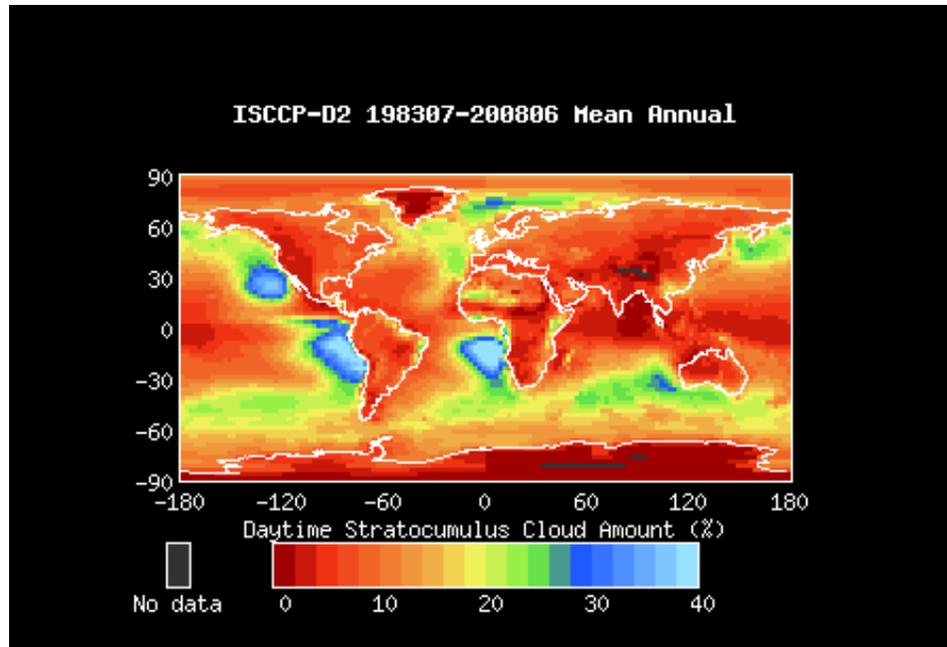


Figure 1. Global mean stratocumulus cover between July 1983 and June 2008. Image provided by ISCCP, NASA, from their web site at <http://www.isccp.giss.noaa.gov>.

There have been difficulties calculating and accurately locating heights of stratocumulus clouds using numerical modeling and remote sensing. General circulation models are unable to correctly reproduce much of the structure and variability of SSTs and convection south of the equator (Cronin et al., 2002). The diurnal changes in the structure of the southeast Pacific stratocumulus cloud-top heights have not been observationally assessed in detail (Zuidema et al. 2009). Therefore, progress at improving our understanding of the lower troposphere over the SEP can be made by obtaining and analyzing data from instruments on ships.

Under the auspices of the Pan American Climate Studies (PACS), instruments were set on ships in a region where little study has been done. The motivations for examining the SEP were to gain a better understanding of the stratocumulus deck, to improve regional and global models, and to enhance climate predictions. Of the eleven cruises between Spring of 1999 and Fall of 2004, the Fall 2000 PACS cruise was studied (explanation later).

Bianco et al. (2008), created an algorithm that uses a multipeak procedure to identify the atmospheric signal in radar spectra. A fuzzy logic picking procedure is then applied to estimate the height of the boundary layer. This algorithm, originally developed to accurately identify the height of the convective BL, was tested to locate the height of the marine BL. The dynamics of the marine BL are quite different from the fair-weather overland convective BL (Nucciarone and Young, 1991). The purpose of this research was to test this algorithm in the marine BL and to find heights—if the height is off by a certain magnitude, all heights should be off by the same magnitude—of the marine BL over the SEP using data from a 915-MHz radar wind profiler using a consistent method. Estimating heights is part of a large project to examine effects of the stratocumulus clouds over the SEP.

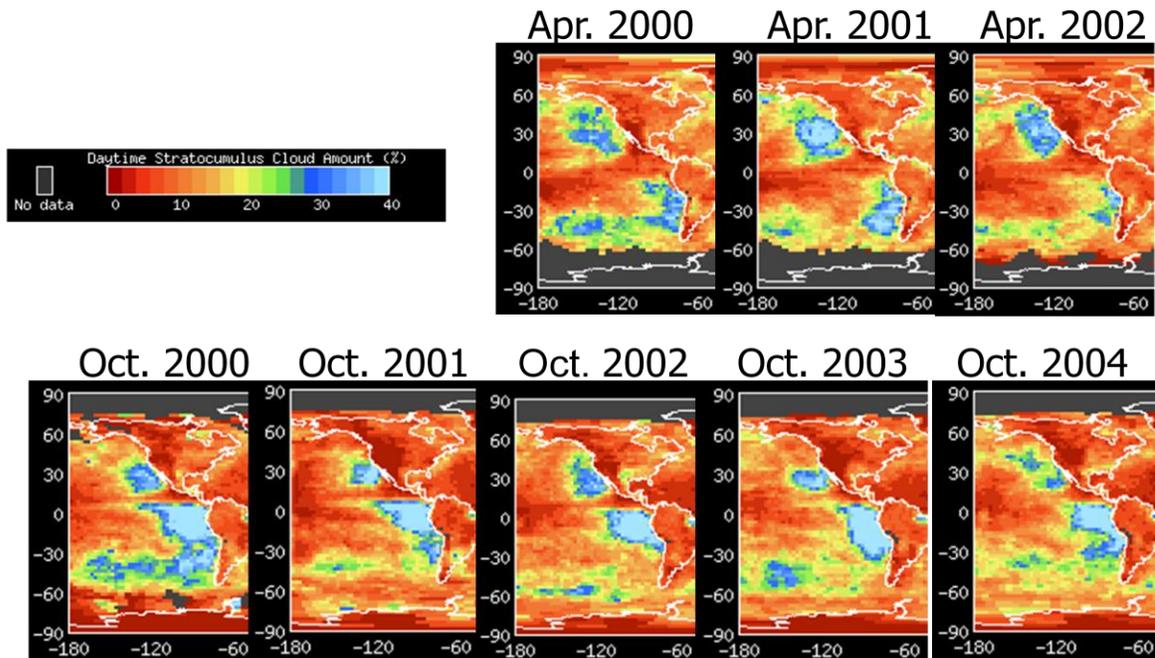
2. Data

A radar wind profiler, along with other instruments, was deployed on the R/Vs *Ronald H. Brown* (Fall cruises) and *Ka'imi Moana* (Spring cruises) to take continuous measurements of the atmosphere while servicing moored buoys in the east Pacific Ocean. Eleven biannual cruises (Figure 2) took place during the Fall and Spring between 1999 and 2004 but only one cruise was used for this study.

There was a large amount of gaps in the profiler data collected from the PACS cruises. In addition to gaps, some cruises only last a few weeks. Cloud forcing, the difference between downwelling radiation observed at the surface and what the radiation would be in the absence of clouds (Cronin et al. 2002), is largest and most variable during the Fall. Data from the Fall 2000 cruise was chosen because of the availability of the data, the length of the cruise, and the amount of mean stratocumulus clouds (Figure 3). Data were collected for 40 consecutive days with only 3 gaps. Also, there were more stratocumulus clouds in the Fall 2000 cruise than the other ten cruises.

Cruise Name (as in ftp directories)	Dates (from "metz" file)	Profiler dates (ddd-ddd)	Profiler (915 MHz) file location (Dyyddd.SPC) (ssyyddd.raw, ssyyddd.rev)
PACS_1999_Fall	303 - 336	2 Nov - 2 Dec (gaps)	300-336 (gaps) Not Deployed
PACS_2000_Spring	111 - 137	20 Apr - 6 May	111-137 (KAI) 111-147 (RBN) Not Deployed
PACS_2000_Fall	291 - 317	17 Oct - 12 Nov	300-324 Not Deployed [disk]**
PACS_2001_Spring	86 - 117	27 Mar - 27 Apr	100-116 No [et6] Files not in [disk]
EPIC_2001 - Leg 1	253 -277	10 Sep - 4 Oct	253-349 (gaps) 254-315 (gaps) [et6]Raw/25 [et6]Raw/SpecMom
EPIC_2001 - Leg 2 (STRATUS 2001)	283-297	10 Oct - 24 Oct	[et6]Raw
PACS_2001_Fall	303 - 336	30 Oct - 2 Dec	253-297 (gaps) 239-297; 303-348 (gaps) [et6]Raw [et6]Raw/ascii [disk]
PACS_2002_Spring	65 - 91	6 Mar - 1 Apr	032-090 [disk]
PACS_2002_Fall	277 - 307	4 Oct - 3 Nov	No [et6] Files
PACS_2003	305 - 324	2 Nov - 20 Nov	296-324 [et6]Raw/SpecMom [et6]Raw/SpecMom/ ascii
PACS_2004	303 - 332	29 Oct - 27 Nov	294-340 [et6]Raw/SpecMom [et6]Raw/SpecMom/ ascii

Figure 2. Part of a data inventory table showing eleven data sets obtained from biannual cruises between Fall 1999 and 2004. Shows available and unavailable data for a 915-MHz profiler.



Images provided by ISCCP, NASA, from their Web site at <http://www.isccp.giss.noaa.gov>.

Figure 3. Monthly mean stratocumulus cover during April 2000-2002 and Octobers 2000-2004 in the eastern Pacific Ocean.

As shown in Figure 4, R/V *Ronald H. Brown* left port in southern California to service the eastern portion of the TAO (Tropical Atmospheric Ocean) buoy array. Data from the TAO buoy array is used by scientists to improve understandings of El Niño and La Niña. Along the 95° W longitude, there are small irregularities where the ship appears to have gone off track. This is a result of the ship fetching buoys that drifted away from their anchored positions. The buoy originally set at 5°N, 110°W broke away, requiring the vessel to greatly deviate from the planned track—southerly along 110°W longitude—to retrieve it.

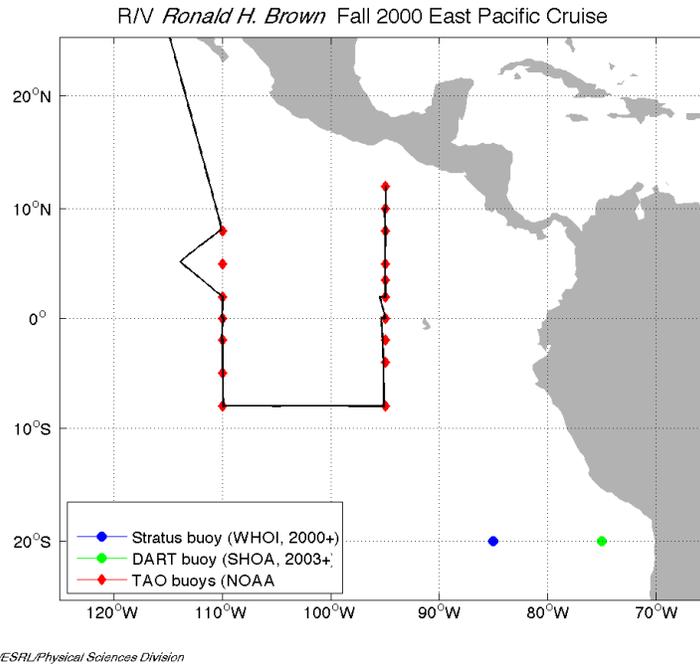


Figure 4. Ship track of the R/V *Ronald H. Brown* between October 12, 2000 and November 20, 2000

Wind profilers are dwelling radars, rather than scanning radars, dependent upon the scattering of the electromagnetic energy by minor irregularities in the index of refraction of the air (Vaisala Oyj, 2004). The area under the curve of the first moment (the largest peak) is the power, which is proportional to the signal-to-noise ratio. The radial velocity is known as the Doppler shift—distance away from 0.0 m/s. Only data from the vertical beam was used for this research, so for simplicity, “vertical velocity” is used in the rest of this paper. Spectral width is the variability of the signal. We can use the intensity of the signal-to-noise ratio, radial velocity, and spectral width to measure the top of a boundary layer (Bianco et al., 2008).

There are many types of radar wind profilers, some distinguished by frequency. The R/V *Ronald H. Brown* was equipped with a 915-MHz radar wind profiler, which detects clear air as well as precipitation. Figure 5 shows a spectrum from an S-band radar at the 5.97 km gate. Signal power is the area below the curve but above the dark line, (i.e. above the Noise Power Level). Radial Velocity is the

first moment of the points in that peak (the points above the Noise Power. Spectral Width is two times the square root of the second central moment—second moment of points after mean is removed—of the points in that peak. Figure 6 shows reflectivity (signal-to-noise ratio multiplied by the range squared), vertical velocity, and spectral width from the vertical beam on November 1, 2000. The color bar was auto-scaled over the full range of the “raw” data, which contains atmospheric as well as non-atmospheric data. For example, radar engineers explained that atmospheric-induced signal-to-noise ratios could not be larger than 30 dB and spectral widths could not be as large as 6 m/s (P.E. Johnston and J. Jordan, 2010, personal communication).

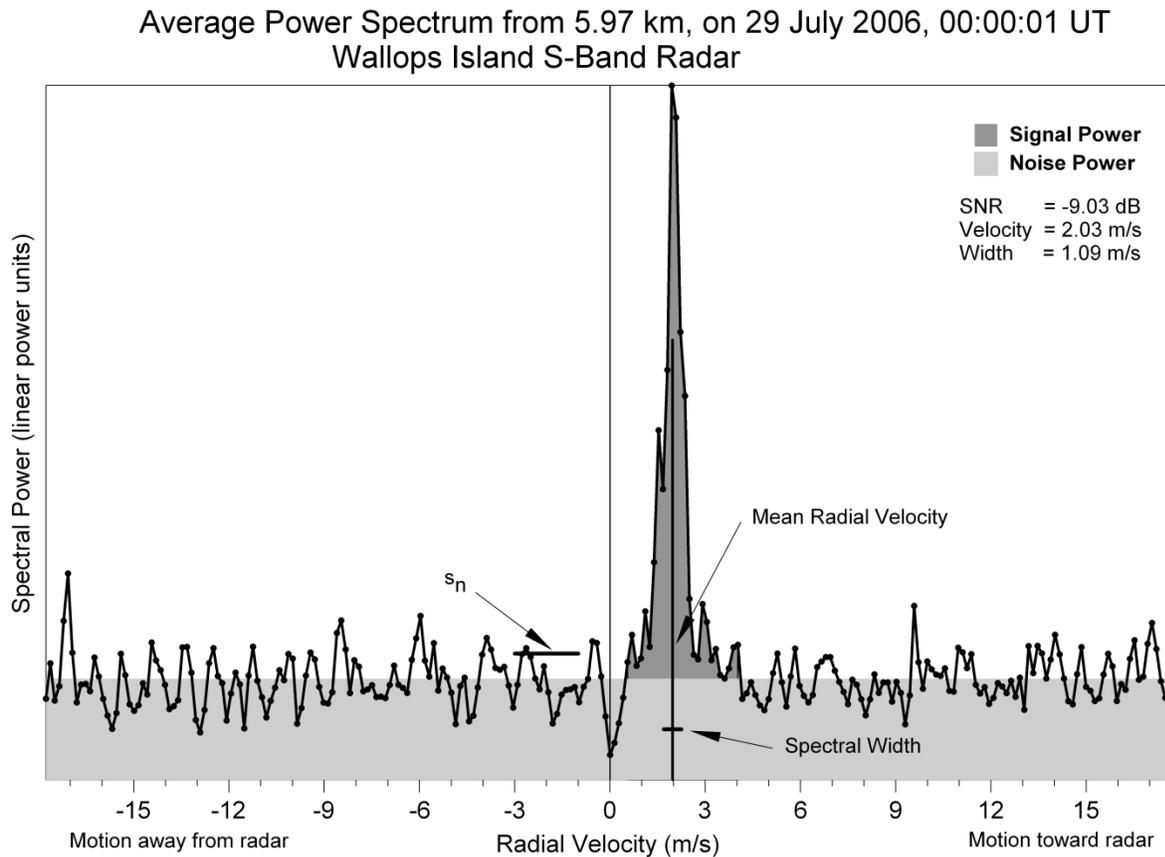


Figure 5. From Riddle et al. (2010). Spectral power as a function of radial velocity for the 5.97 km gate using an S-band profiler

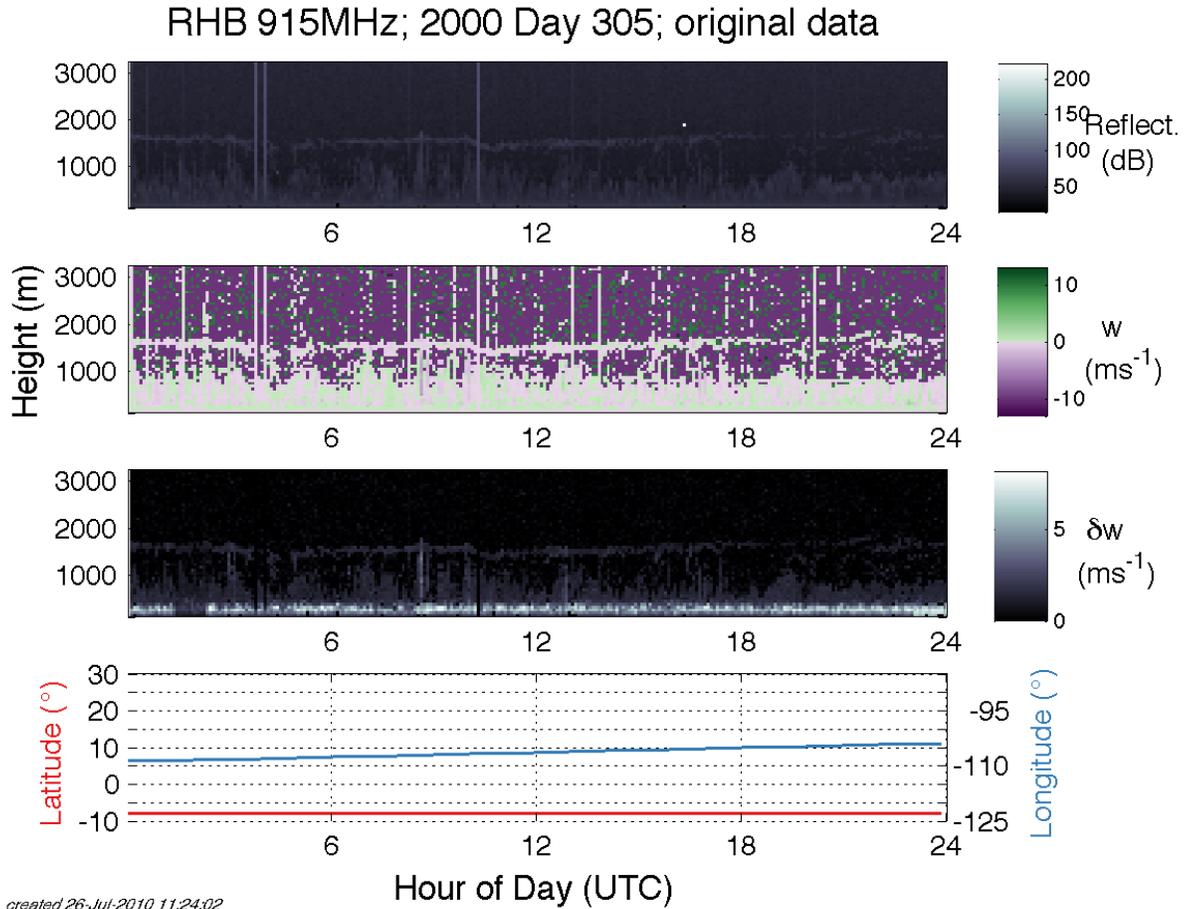


Figure 6. "Raw" profiler data, showing reflectivity, vertical velocity, and spectral width as functions of time and height for November 1, 2000.

3. Techniques

In order to see atmospheric structures, as much non-atmospheric data as possible need to be removed. A minimum threshold of signal-to-noise ratio (SNR) detectability was developed by Riddle et al. (1989) (Figure 7a). This would clean out much of the "bad" data, leaving atmospheric signal. Subtracting 1.5 dB from Riddle's threshold resulted in a beneficial tradeoff of a lot more "good" data points for inclusion of a few more "bad" data points. Therefore, when signal-to-noise ratio was less than Riddle minus 1.5 dB, all three variables were set to NaN (Figure 7b). There were also other factors that led to variables being set to NaN. If spectral width was larger than 3 m/s, spectral width and signal-to-noise

ratio were set to NaN. Radar engineers explained a SNR higher than 30 dB was likely to be non-atmospheric and should be set to NaN.

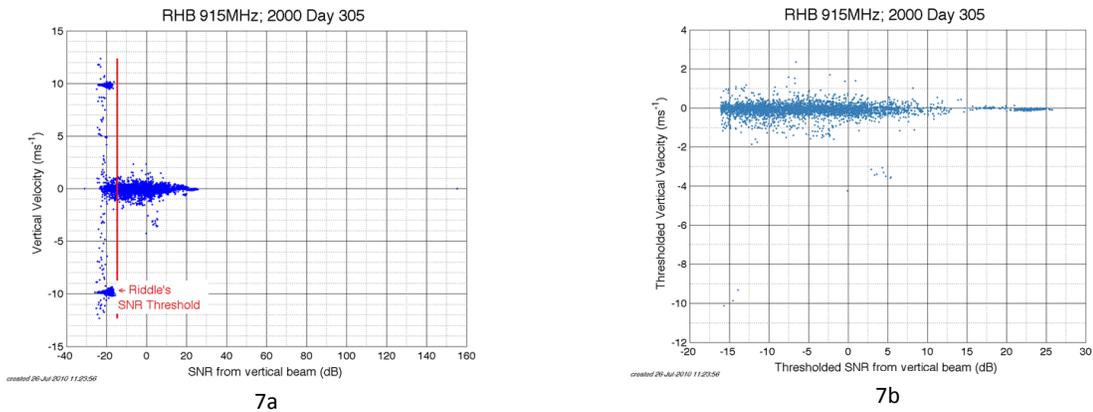


Figure 7. Vertical velocity as a function of signal-to-noise ratio. (a) “Raw”. Riddle’s minimum threshold of detectability divides signal (to the right of the vertical red line) from noise (to the left of the red line). (b) “Thresholded” data (removed SNR < Riddle - 1.5 dB, SNR > 30 dB, SNR if spectral width > 3 m/s).

Figure 8 shows a before and after count of vertical velocity values. Figure 8a is before thresholding, showing obvious peaks of non-atmospheric data at 10 and -10 m/s. After clearing out non-atmospheric data, figure 8b shows what remains.

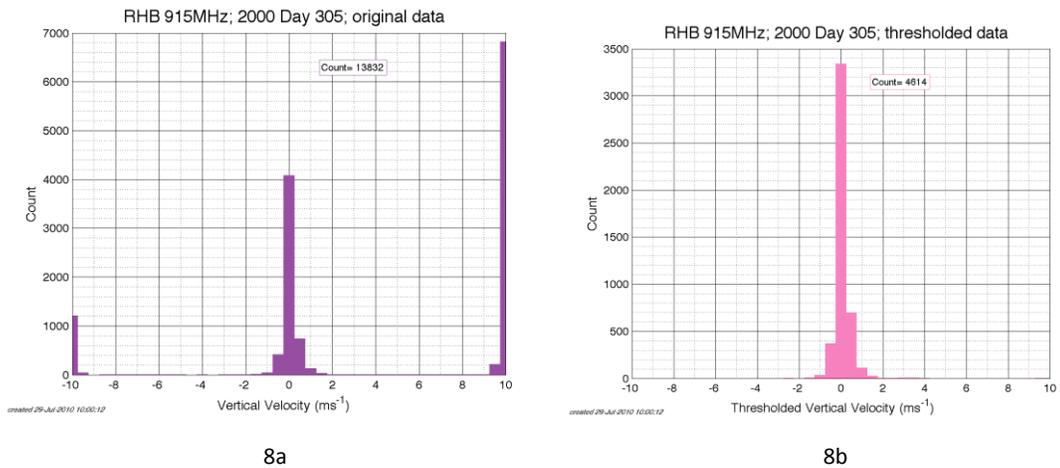


Figure 8. Histograms of Vertical Velocity for day 305 (November 1, 2000) (a) before thresholding; (b) after thresholding

4. Results

The Bianco et al. (2008) algorithm uses hourly mean vertical profiles of reflectivity, vertical velocity variance, and spectral width of the vertical velocity from the wind profiler in a fuzzy-logic-picking procedure to estimate the height of the *convective* BL over land. In this research, the algorithm was tested in a *marine* BL region (SEP), and on data collected from a moving platform. A set of heights and confidence scores has been created by the Bianco et al. (2008) algorithm for the entire cruise. Figure 9 shows plots of the data shown in Figure 6 after thresholding along with the estimated BL heights. The heights closer to the ground are probably wrong, which is attributed to an average of meager data closer to the surface. Of twenty-seven days with data, twenty-two had estimated heights, where ten of those days included heights near the ground that are nonsensical and not plausible. Of the twenty-two days with heights, there were twenty-one with at least one realistic height (there was one day with only one height and it was not reasonable).

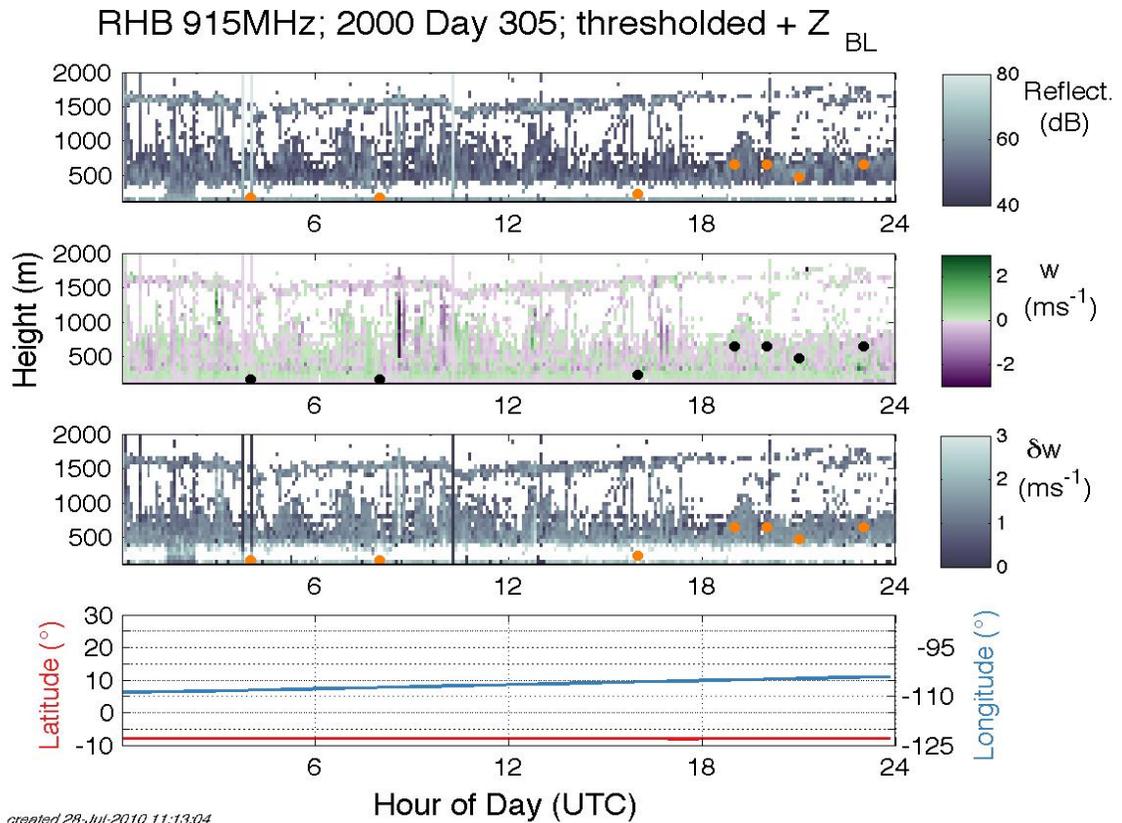


Figure 9. “Thresholded” profiler and ship data, showing reflectivity, vertical velocity, and spectral width as functions of time and height for November 1, 2000. Colored dots indicate estimated BL heights.

Although there are twenty-four hours in a day, there are only height estimations for seven hours on day 305. Most days had only one plausible height while the maximum number of estimated heights was 13. The average number of heights per day for the twenty-two days with heights was four. This can be explained in a brief example: the space of missing data at 12 UTC below 500m (but just above the surface) in the Reflectivity plot was not interpolated across to give an estimated height. Therefore, no large spaces were interpolated in order to ensure a higher confidence score of the estimated height. Because the *marine* BL data does not have the same characteristics as data from the *convective* BL, the algorithm’s confidence for the heights it detected was low. Therefore, the algorithm needs adjusting to incorporate the expected marine BL structures. The results will also likely improve with further cleaning of the data (P.E. Johnston, 2010, personal communication).

5. Discussion

Radar engineers are still skeptical of some of the data that remained after obvious non-atmospheric data were cleaned out (e.g. the low-velocity, high-SNR points in Figure 5b). This leaves more work for data cleaning. Also, the algorithm needs further modifications in order to adapt from a convective BL to a marine BL. When these two tasks are completed, BL heights can be recalculated and then verified against other data from the cruise (balloon soundings, ceilometer, etc.). After obtaining heights from all cruises, radiation budget effects can be looked at as functions of cloud depths.

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