Reflectivity Gradients
in the Lower Troposphere Over the Tropical Pacific:
A Climatology Based on Wind Profiler Data

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ABSTRACT

Studies of reflectivity gradients are necessary to understand the factors affecting wind profiler measurements. Wind profiling radars reflect radio waves from atmospheric variations in the lower troposphere and are used to measure winds. The change in these reflectivities over a given range is referred to as the reflectivity gradient. This research examined the vertical structure and variability of the reflectivity gradients, using data collected from 915-MHz wind profilers in Galápagos (0.90° S, 89.57° W) and Tarawa (1.36° N, 172.92° E). Past studies have found inconsistencies in velocity profiles, due to incorrect height assignments caused by invalid assumptions about the atmospheric reflectivity gradient. Analysis of monthly mean reflectivity gradients indicated cycles of variability at the two sites. In Tarawa, there were periods of an annual cycle as well as an El Niño-Southern Oscillation (ENSO). Galápagos data indicated hints of an annual cycle. Overall, the vertical structure of the reflectivity gradient appeared the same in both sites, although Galápagos had insufficient data for a detailed analysis. The atmospheric reflectivity gradient was fairly constant above 1.5 km but was large and negative below 1.5 km. There were significant differences in the mean reflectivity gradients beyond 1.5 km range in some of the meteorological seasons and ENSO phases. A reasonable assumption for the reflectivity gradient beyond 1.5 km is approximately -1.85 dB km⁻¹. The results of this research further the understanding of the structure of the reflectivity gradient and the different cycles of variability in the tropical Pacific.
1. INTRODUCTION

Wind profilers are pulse-Doppler radars that measure the wind speed and direction in the lower troposphere. A wind profiler sends out radio waves that reflect off variations in the atmosphere. Profilers measure the power of the signal returned, which is related to its atmospheric reflectivity (Carter et al., 1995). The reflected signals are assigned to the center of a volume that is homogeneous, and the distance from the base of the profiler to the center of the volume is known as the range (Figure 1). As another result of the volume being homogeneous, the relative reflectivity gradient (M) within this volume is assumed to be zero (Doviak and Zrnic, 1993). This assumption is typically made by the wind profiling community.

![Diagram](image)

Figure 1. An example of a five-beam profiler system. The profiler data used in this study are from a three-beam system (e.g. using only the light-colored beams). Courtesy of Ahoro Adachi.

Profilers collect data over various ranges with different resolutions. Hartten and Gage (2000) examined data from a profiler on one of the Galápagos Islands. The profiler collects data in two different operating modes: a low mode has a smaller pulse length and gives very high resolution data while a high mode has a larger pulse length and gives coarser resolution data. Hartten and Gage studied velocity profiles from the Galápagos Islands and made note of inconsistencies between the profiler’s operating modes. The problem was that the profiler captured the same features in both modes but assigned them to different heights. Figure 2 is an example of a seasonal mean-profile that shows the inconsistencies in the profiler data. The two lines representing the high and low modes show similar features, but these features occur at different heights. In all actuality, the two modes should be similar because they are surveying the same atmosphere.

Johnston et al. (2002) have shown that the standard assumption that the relative reflectivity gradient is zero may have caused discrepancies in the height assignments. They gave a theoretical explanation for differences in the reflectivity gradient and proposed a correction scheme for the standard radar equations. Coleman (2002) applied the new scheme of the radar equation to adjust height assignments from the Galápagos Islands. He found that applying this general radar equation to the height calculations using the simple assumption that the reflectivity gradient was about \(-2.17 \text{ dB km}^{-1}\) reduced the amount of discrepancies in the two modes.
Figure 2. Seasonal mean profiles of wind speed and direction from a 915-MHz profiler at San Cristóbal, Galápagos. The solid lines are high-mode winds, dashed lines are low-mode winds, and solid circles are surface winds (Harten and Gage, 2000)

Little information about the atmospheric reflectivity gradient is available in the scientific literature. Coleman's assumed profile of reflectivity gradients of $-2.17 \text{ dB km}^{-1}$ came from a derivation by Doviak and Zrnic (1993). This unique study is a continuation of the studies by Coleman (2002) and Johnston et al. (2002). The goal was to examine the relative reflectivity gradient from a climatological perspective. The results will give a better perception of the structure and variability of the reflectivity gradient and will be useful for understanding the structure of the atmosphere. It may also assist in correcting the 10-15 year data archive.

Section 2 of this paper presents the methods employed in the analysis. Results and discussion will be presented in Section 3. Conclusions and future work will be described in Section 4.

2. DATA AND METHODS

The wind profilers used in this research are three-beam systems located in the tropical Pacific and deployed by the NOAA Aeronomy Lab (AL). Although the profilers are three-beam systems, only data from the two oblique beams were used, since reflectivity gradients from the vertical beam may have problems due to signal processing (P. E. Johnston, 2003, personal communication).

Two sites were chosen in the eastern and western Pacific since the atmosphere and its cycles of variability are different in the east and west. Examples of this variability include the different effects of ENSO and the annual cycle in the eastern and western tropical Pacific. San Cristóbal, Galápagos, in the Eastern Pacific, was chosen for this study because it was used previously by Hartten and Gage (2000) and Coleman (2002). Manus, Nauru, or Tarawa were the possible sites in the western Pacific. To decide which site to use, data from the Southern Oscillation Index (SOI) and the Sea Surface Temperature (SST) data from January 1992 to December 2001 for Manus, Nauru, and Tarawa were compared. The SOI and SST data were used to see if there were data available during various phases of ENSO. An inventory of the data
was used to see how many months each site had data and to compare it with the data from Galápagos. The profiler at Tarawa was chosen as the western Pacific site because its data coverage most overlapped with the Galápagos coverage.

Half-hourly means were used to complete this research. Since a climatology was being performed, half-hourly data are more comprehensive than the original three minute data, and allow one to cover a longer period. Another reason individual scan data were not used is because it will be more logical to correct the half-hourly data that is archived. Furthermore, analyzing the individual scan data would be extremely time consuming.

The data used were post-processed at NOAA/AL as described in Riddle et al. (1996). Data were only used if there was clear air because clouds and precipitation affect the reflectivity gradients. The 915-MHz profilers at the two sites operate in low and high modes. Low mode data were not used below 500 m (≈4.8 pulse lengths) and high mode data were not used below 1400 m (≈2.8 pulse lengths) because the profiler is unable to receive good reflectivities at these heights. Other specifications of the data were that the threshold for the signal-to-noise ratio be greater than or equal to −11 dB km\(^{-1}\). This constraint was put on the data because there is a minimum detectable signal (P. E. Johnston, 2003, personal communication).

A gradient is calculated by dividing the difference of what is being measured by the distance (in time or space) over which it is measured. For example, the temperature gradient over a distance is computed by taking the temperature difference, \(\Delta T\), and dividing it by the difference in distance, \(\Delta D\). Since reflectivity is in log space (dB are logarithmic units), you cannot take a simple difference. The following derivation provides the details on how to calculate the reflectivity gradient, \(M\) (P. E. Johnston, 2003, personal communication). Note that the changes are in range, the distance along the beam, not in height.

\[
M(r_i) = 10 \times \log \left( \frac{\eta(r_i)}{\eta(r_2)} \right) \quad (1)
\]

where the reflectivity \(\eta\) can be found in the following way and SNR is the signal-to-noise ratio

\[
\eta(r) = \text{SNR}(r) \times N(r) \times r^2 \quad (2)
\]

\(N(r)\), the noise, is assumed independent of range so

\[
\eta(r_i) = \text{SNR}(r_i) \times N \times r_i^2 \quad (2a)
\]

\[
\eta(r_2) = \text{SNR}(r_2) \times N \times r_2^2 \quad (2b)
\]

Therefore,

\[
M(r_i) = 10 \times \log \left( \frac{\text{SNR}(r_i) \times N \times r_i^2}{\text{SNR}(r_2) \times N \times r_2^2} \right) \quad (3)
\]

\[
= 10 \times \log \left( \frac{r_i}{r_2} \right)
\]
\[
M(r_i) = \frac{10 \times \log(SNR(r_i)) - 10 \times \log(SNR(r_2)) + 20 \times \log\left(\frac{r_1}{r_2}\right)}{(r_1 - r_2)}
\]

After compiling the reflectivity data, a subset was selected for the initial study. The months for the profiles were chosen based on data availability. The middle month of each standard meteorological season was chosen since those months had the most data and this allowed even sampling of the annual cycle. The months selected were October, January, April, and July, for boreal fall, winter, spring, and summer, respectively. The period of record was from October 1994 to April 2001. Data from both Galápagos and Tarawa are available for the time periods studied by Coleman (2002); some gaps in the data include November 1995 to July 1996 in Galápagos and April 1996 to November 1996 in Tarawa. Within the months selected for sampling, there are relevant events that might cause variability in the lower troposphere. The time periods from October 1994 to October 1995 and October 1996 to October 1999 encompass four full annual cycles. Looking at the five-month running mean (five months averaged) of Southern Oscillation Index enabled us to see if conditions of El Niño or La Niña take place. If the SOI is greater than +1, La Niña conditions are assumed, and if the index is less than −1, El Niño conditions are expected (Figure 3). SOI values between −1 and 1 signify normal conditions. There is a period of El Niño from March 1997 to March 1998. Periods of La Niña are found from August 1998 to February 1999 and around November 1999 and November 2000.

Figure 3. Plot of the Southern Oscillation Index October 1994 to October 2001 (5-month running mean applied).

3. RESULTS AND DISCUSSION

Throughout this research, many plots were developed and analyzed to examine the structure and variability of the reflectivity gradient. During the analysis of these plots, we found results that were related to the original goals as well as other results that can be used for further studies.
3.1 Similarities in Profiler Beams

To understand reflectivity gradients more, it was necessary to determine whether separate calculations of reflectivity gradients from each of the profiler's oblique beams were required or if a combination of the beams could be used. To do that, the monthly means of reflectivity gradients of the low and high modes were plotted for each of the profiler's beams at Tarawa and Galápagos. These means were calculated from all available data, regardless of range, subject to the constraint discussed in section 2. The results showed that the reflectivity gradients on the beams were almost identical, with some minor exceptions. Because the reflectivity gradients were so similar, a decision was made to use the combined data from the two beams (Figure 4). The results have also shown cycles of variability at the two sites in the monthly mean reflectivity gradients. In the Tarawa means there appears to be a period of the interannual cycle (ENSO) around 1997, as well as the annual cycle from 1998 to 2001. This inference agrees with data from the Southern Oscillation Index (SOI), which shows a severe El Niño event occurred. Then in Galápagos, there is a hint of the annual cycle from 1996 to 1997. From 1998 to 2001 there was a good amount of small-scale variability as well as less agreement between the two profiler beams. This variability is possibly due to instrument issues.
Figure 4. Plots of monthly mean Tarawa high mode and Galápagos high mode reflectivity gradients, computed using data from all ranges. M1 and M2 are the reflectivities from each of the individual profiler beams and M1&2 is the combined reflectivity.

3.2 Number of Observations

Although the number of observations at Galápagos and Tarawa was not a concern in the initial setup of the research, it became an issue when analyzing the monthly means of reflectivity gradients. It became apparent that the data from the Galápagos looked suspicious and that the profiler was not receiving adequate data. The number of observations were plotted for both sites and we found that since the initial setup of the profiler in Galápagos, there has been a decline in the number observations as well as a degradation in the profiler performance (Figure 5). Since the performance of the profiler has declined in the past years, money has been granted for repairs. Results found about the number of observations have sparked ideas on what repairs need to be made. Members of the NOAA Aeronomy Lab have begun to take a closer look at what could be happening to the profiler in the Galápagos, and a trip to repair and enhance the system.
is scheduled for fall 2003. The number of observations in Tarawa varies but does not show a trend.

**Figure 5.** Plots of the number of observations for Galápagos high and low mode reflectivity gradients. M1 and M2 represent each of the two oblique profiler beams.

### 3.3 Mean Profiles of Vertical Structure

Mean profiles of reflectivity gradients were plotted for Tarawa and Galápagos, so that the vertical structure of the gradients could be analyzed. When looking at the Tarawa mean profiles from 1994-2001, the patterns of the vertical structures were the same. Most of the Tarawa plots had good height coverage but the best coverage was found in July 2000. Since July 2000 had the best coverage, it was chosen for the full analysis (Figure 6). The mean reflectivity gradient is on the x-axis and ranges from −30 to 30 dB km\(^{-1}\) the range is from 0 to 6 km. The low mode is represented by the red line and the high mode is represented by the blue line. From 0.6 km to 1.4
km, the mean reflectivity gradient is a large negative number and then it begins to increase towards more positive gradients of reflectivity. Since there were large negative numbers of reflectivity gradients in the beginning of the low mode profile, there are possibly some instrument issues or even a boundary layer process affecting those measurements. Further studies on reflectivity gradients are needed to see what may be causing these large negative values. Therefore, my analysis of the reflectivity gradient begins at about 1.5 km. After a range of 2 km, the gradient settles within the envelope of −5 to 2 dB km⁻¹ until the low mode reaches 4.2 km. The high mode ranges from 2.2 to 5.2 km. The high mode follows the same path as the low mode but the line is a lot smoother because the high mode has a longer pulse length.

![Graph](image)

*Figure 6. Tarawa July 2000 profile of the mean reflectivity gradient. The red line represents high mode and the blue line represents the low mode.*

The vertical structure of the reflectivity gradient for Galápagos was harder to analyze due to an insufficient amount of data after 1995. The Galápagos profile from January 1995 was the closest profile that was similar to the Tarawa profiles (Figure 7). The low mode range is from 0.6 to 2.4 km and the high mode ranges from 1.8 to 4.3 km. Again, the low mode starts with large negative values and then increases towards a positive reflectivity gradient. Then from 1.5 to 2.3 km, the reflectivity gradient oscillates between positive and negative reflectivity gradients. During this range the gradient settles within the envelope of −5 to 5 dB km⁻¹. The high mode follows the same path as the low mode, and the high mode is smoother due to the longer pulse length.
Figure 7. Galápagos January 1995 profile of the mean reflectivity gradient. The red line represents the high mode and the blue line represents the low mode.

3.4 Profiles of Reflectivity Gradients

There have been many assumptions for the actual value of the reflectivity gradient. The wind profiling community made the assumption that the reflectivity gradient was zero because the gradient is observed within a volume. Since this volume is assumed homogenous, the reflectivity gradient would then be zero. As stated in section 1, Coleman (2002) used the assumption that the reflectivity gradient was approximately $-2.17$ dB km$^{-1}$. To come up with an approximate value of the reflectivity gradient, I needed to recalculate the monthly means. The Tarawa low mode means for the range above 1.5 km were used in this recalculation. I calculated that the overall mean reflectivity gradient was approximately $-1.85$ dB km$^{-1}$. Figure 8 shows the assumptions used by the wind profiling community, Coleman, and my calculated value. These monthly means were averaged into categories: the overall mean, the means of the meteorological seasons, and the means of El Niño and La Niña conditions. Table 1 shows the various averages calculated from the monthly mean reflectivity gradients.
Figure 8. Profile of values of reflectivity gradients. The blue dots represent the assumption made by the wind profiling community and the red line is the assumption used by Coleman. The green line is my calculated value.

<table>
<thead>
<tr>
<th></th>
<th>mean (dB km⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>overall mean (10/94-4/01)</td>
<td>-1.85</td>
</tr>
<tr>
<td>D/J/F only:</td>
<td>-2.37</td>
</tr>
<tr>
<td>M/A/M only:</td>
<td>-0.98</td>
</tr>
<tr>
<td>J/J/A only:</td>
<td>-1.82</td>
</tr>
<tr>
<td>S/O/N only:</td>
<td>-2.22</td>
</tr>
<tr>
<td>SOI &lt;= -1 only (El Niño):</td>
<td>0.24</td>
</tr>
<tr>
<td>SOI &gt;= +1 only (La Niña):</td>
<td>-3.79</td>
</tr>
</tbody>
</table>

Table 1. Table of the averages calculated from the monthly mean reflectivity gradients. The left-hand column represents the categories of averaged monthly means and the right-hand column represents the calculated means.

To see if there were significant differences between the means, a two-tailed student's t test was conducted. The confidence level for the difference in the means is 0.01. Comparisons of the D/J/F mean vs. the M/A/M mean and SOI <= -1 vs. SOI >= +1 indicated that there were significant differences between those means.

IV. CONCLUSION

Compiling a climatology of the reflectivity gradients allows us to get a better understanding of their vertical structure as well as different cycles of variability. Results indicated that there were similarities in the reflectivity gradients from the profiler’s oblique beams. This result helped to minimize the workload for this research. It also verified the assumptions made by the profiler community that atmospheric conditions in the two beams are similar. Discovery of a decrease in the number of observations in Galápagos has led to further studies on the operating status of the profiler in Galápagos. Although this research did not include a complete side-by-side comparison of the vertical structure of the reflectivity gradients.
at Tarawa and Galápagos, results have shown that the basic vertical structure is consistent in Tarawa. Beyond 1.5 km the atmospheric reflectivity gradient is nearly constant and my calculation of $-1.85 \, \text{dB km}^{-1}$ falls between the standard assumption of 0 made by the wind profiling community and Coleman’s assumption of $-2.17 \, \text{dB km}^{-1}$. There was significant variability in the mean reflectivity gradients for the meteorological seasons (D/J/F vs. M/A/M) and for El Niño and La Niña conditions.

Further research is needed on the structure of the reflectivity gradients at other sites. The profiler in the Galápagos needs repairing so that a further analysis of the reflectivity gradient can be explored.

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REFERENCES


