Analysis of Seasonal and Diurnal Variability in the Planetary Boundary Layer using GPS Radio Occultation Data

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Abstract.

GPS Radio Occultation (GPSRO) is a remote sensing technique used to measure precise vertical atmospheric structure even in the presence of cloud cover. The Planetary Boundary Layer (PBL) forms a crucial component of the atmosphere, with significant impacts on global energy and water cycles. As the closest part of the atmosphere to the surface of the Earth, the PBL plays a significant role in governing heat exchanges and low-level cloud formations. Using five years of data (2007-2011) from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellite constellation, the seasonal and diurnal variations in PBL height were analyzed for regions in the Northeast and Southeast Pacific Ocean. After developing algorithms to determine PBL height from GPSRO profiles, the data was then sorted and filtered based on various time constraints to study seasonal and diurnal cycles. Different signal processing and time-frequency analysis techniques were explored to provide insight into the periodic nature of PBL variation. GPSRO results were then validated via cross-reference with weather reanalysis data.

1. Introduction

The Planetary Boundary Layer (PBL) is the part of the atmosphere closest to the earth. In particular, it is the atmospheric structure most actively involved in the formation of low-level clouds and heat fluxes between the earth and free troposphere. Due to its effects on global energy and water cycles, it is critical to understand its behavior when developing accurate weather models (*Medeiros et al.* [2005]).

Since the PBL is an important component in weather models, climate scientists and meteorologists have turned to remote sensing techniques to understand its properties. GPS Radio Occultation(GPSRO) has recently emerged as a powerful technique to measure atmospheric structure, with many advantages over other methods of remote sensing. GPSRO has a high level of precision and a significant degree of vertical resolution. Furthermore, GPSRO does not rely on an absence of cloud cover over the region being studied, because the signals used, L-band microwave, can pass through weather media with negligible deflection. Given these unique advantages over other satellite remote sensing technologies, GPSRO has promising application to the study of PBL height.

Recent satellite missions have enabled studies on the PBL. For example, the PBL height has been characterized through aerosol backscattering techniques with data from the CALIPSO satellite mission (*Jordan et al.* [2010]). Data from aerosol backscattering, however, often results in high-noise, low-precision estimates. GPSRO measurements offer numerous benefits over this technique because the level of vertical precision is much higher. Recent studies have formed basic PBL height climatologies using COSMIC radio occultation data (*Ao et al.* [2012], *Guo et al,* [2011]). Developing a time-sensitive model for PBL height remains an open problem in climate science and the variability of PBL height in various timescales has not been thoroughly analyzed, particularly not with GPSRO derived estimates.

In this study, we analyzed the diurnal and seasonal variation in PBL height estimates from GPSRO measurements, focusing on subtropical regions in the Pacific Ocean. These regions were chosen because they allow for validation of results with documented local weather patterns and historical weather data of these regions. Using five years of COSMIC radio occultation data, we quantified the degree of seasonal and diurnal variability in the PBL height and compared results to those obtained from historical weather reanalysis data for the regions. We found that GPSRO data allows for accurate measurements of PBL heights, with ample sampling frequency for robust analysis of PBL variability. We also found that results from GPSRO data aligned with weather reanalysis data and local climate patterns, suggesting the viability of this application of GPSRO.

2. Approach and Methods

The PBL to free troposphere transition zone is characterized by sharp changes in temperature and water vapor. Refractivity, which is a function of both temperature and water vapor, is therefore an important indicator of PBL depth. By studying refractivity profiles for a region, we can determine a PBL height climatology. Figure 1 provides a sample refractivity profile from a single GPSRO measurement.

2.1. Algorithm I

We developed a basic algorithm to derive a PBL height from a single refractivity profile. This was the primary algorithm used in analysis.:

2.1.1. Algorithm I procedure

1. Perform cubic interpolation to achieve a 10-meter vertical resolution

2. Set a height ceiling of 3.0 km to avoid selection of unrealistically high PBL heights

3. Compute the first derivative of refractivity via centered difference quotient about each point

4. Find local minima of the refractivity gradient profile, checking that these minima are less than 65 N-units per km.

5. If 3 or more such local minima exist, report no PBL height. Otherwise report the location of smallest refractivity gradient as PBL height

This algorithm was applied to two different sets of GPSRO data. We used data from the COSMIC constellation of satellites, specifically occultations performed during the five-year span of 2007-2011 in 10-degree square latitude longitude grids in the Northeast Pacific Ocean and Southeast Pacific Ocean.

2.2. Algorithm II

In addition to the primary algorithm, we examined a second algorithm. We initially considered this alternative to account for the fact that the first algorithm may occasionally select high level inversion layers as a PBL height. This second algorithm reported lower

PBL heights, as expected, as well as similar variation in the time series of PBL heights.

2.2.1. Algorithm II procedure

1. Perform cubic interpolation to achieve a 10-meter vertical resolution throughout the profile.

2. Set a height ceiling of 3.0 km to avoid selection of unrealistically high PBL heights

3. Compute the first derivative of refractivity via a centered difference quotient about each point

4. Find all local minima of the refractivity gradient profile at which the spatial gradient less than 65 N-units per km.

5. Select the minima that occurs at the lowest altitude.

3. Results

We applied the first algorithm to the complete occultation data sets. Despite significant noise, we noted a level of periodicity in reported PBL heights (Figure 2 and Figure 3). In particular, there is visible periodic variation about the mean PBL heights. However, there also appeared to some potential outlier bias. The selection of outliers suggests that we could preprocess the data more stringently and investigate if outlier selection occurs because of our choice of PBL-height algorithm or if it corresponds to actual weather phenomena. For example the SE Pacific region yielded a range in PBL heights between 0.5 km and 2.9 km, and occultations performed only a few days apart exhibit this range.

To determine seasonal variability, we studied composite years of the results and performed fitting and filtering techniques to extract seasonal trends. The full data sets were averaged across the calendar day when the measurement was taken. After applying a one-dimensional Gaussian filter to the time series, we recovered a smoothed version of the data. In addition, a sine function was fitted to the data, with a single term of the form

$$S(x) = a\ sin(T\,x + p) + c,$$

where $T = 365$ days, to determine the variability over the course of a given years. This allows to directly quantify amplitude and phase for the variation. The Gaussian filter and sinusoidal fitting methods produced similar results in terms of isolating the variation of the PBL height over a yearly timescale (Figure 4 and Table 2). The composite year sinusoidal amplitudes were 0.101 km and 0.112 for the NE Pacific and SE Pacific regions respectively. In addition, we found phases of 114 days for the NE Pacific and 13.5 days for the SE Pacific.

To ascertain diurnal cycles, we employed a similar approach (Figure 5 and Table 3). Each data set was sorted based on the local time when the occultation was performed. Again, data was subject to Gaussian smoothing and sinusoidal fitting. We found that PBL heights were lowest in early morning and peaked in late afternoon; the SE Pacific region in particular strongly demonstrated this pattern. The NE Pacific sinusoid fit had a phase shift of 6.23 hours, while the SE Pacific fit had a phase shift of -0.787 hours with a negative amplitude. Local climate patterns provide intuition for this result because these regions often have low-level marine layers in the morning, which burn off by the afternoon. The PBL height in turn changes to reflect this weather phenomenon.

We compared our GPSRO results to those obtained from data from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses. This weather reanalysis database provided refractivity profiles similar to those obtained from GPSRO, and we could apply our algorithm to validate the GPSRO results. Comparing ECMWF refractivity profiles and the GPSRO data were compared showed a high level of covariance in the time series. With composite year comparisons, evidence of a systematic difference is apparent (Figure 6). PBL estimates obtained from GPSRO data were often uniformly higher by a fixed amount than those reported from ECMWF data. While the variability in time is similar, the actual heights are different due to this error. The fitted sinusoids yield relatively similar phase shifts for the yearly timescale. For example, the SE Pacific region had a yearly phase shift of 7.5 days when we looked at GPSRO data, while the ECMWF data had a phase shift of 33 days. Therefore, ECMWF data produced very similar *variability* to GPSRO results, however it demonstrated a much smaller amplitude of this variation, which we can attribute to systemic error. This suggests that the algorithm could be refined to correct for this error and would allow us to achieve near-identical results between GPSRO and ECMWF data.

We also investigated differences between the two algorithms outlined in the Methods (Figure 7). Initially implemented to correct for the potential of the first algorithm to select higher altitude refractivity inversions, the second algorithm provided noteworthy insight into the ability of GPSRO to measure variability in the layering of the PBL. In particular, we could continue to develop this algorithm to study stratification in the PBL itself.

4. Conclusions

The study yielded four primary conclusions. First, GPSRO reported PBL heights that reflect the local climatologies for both of the regions studied. It is well documented that maximum cloud cover occurs during the June-July-August quarter for the Northeast Pacific Region and September-October-November quarter for the Southeast Pacific (*Wood* [2012]). GPSRO data yielded consistent results for the respective macro-climate characteristics of the regions.

Second, diurnal cycles appear to be consistent to those reported in the literature. The SE Pacific in particular has been examined extensively, with studies utilizing both *in situ* measurements and weather analysis data. These studies found that PBL heights generally are lowest in early morning and then peak by late afternoon (*Rahn and Garreud.* [2010]). We confirmed these results with GPSRO data.

Third, seasonal and diurnal cycles were similar between GPSRO and ECMWF data sets, though ECMWF results had lower amplitude and lower mean. There appears to be a systemic error between the GPSRO data and the ECMWF data. The underlying reason for this disparity provides grounds for further study. It primarily highlights potential shortcomings of analysis projects such as ECMWF.

Fourth, implementation of a second PBL height algorithm showed that choosing the lowest occurring minimum of refractivity gradient yielded similar seasonal and diurnal cycles to those of the primary algorithm. This second algorithm also demonstrated the ability of GPSRO to capture insight into layering and mixing in the PBL and suggests that changing the criteria of the PBL height algorithm can capture dynamic atmospheric structure. Algorithm selection thus serves as a good topic for further study.

While there is room for refinement of the algorithms developed here, as well as for the introduction of more robust mathematical methods in evaluating the time-series of PBL heights, we have demonstrated the viability of GPSRO as a means to derive time-dependent PBL climatologies.

Appendix A: Acknowledgments

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Appendix B: Bibiliography and References

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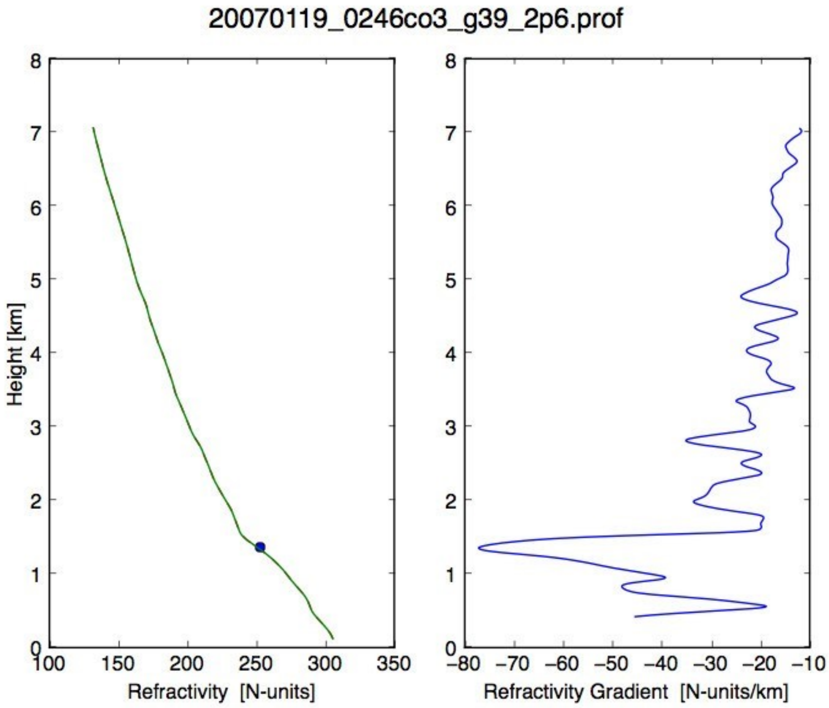

Figure 1. Sample refractivity profile. The PBL depth is characterized by a sharp change in the refractivity, demonstrated in the right graph.

Table 1. Baseline Results for GPSRO data

Region	Mean PBL(km)	Median PBL(km)	Std. Dev. (km)
NE Pac.	1.4818	1.4573	0.4585
SE Pac.	1.4191	1.3841	0.3928

Table 2. Composite Year: Parameters of sinusoidal fitting

Region	a(km)	p(days)	c (km)
NE Pac.	0.101	114	1.48
SE Pac.	0.112	13.5	1.42

Table 3. Diurnal Variation: Parameters of sinusoidal fitting

Region	a(km)	p(hours)	c (km)
NE Pac.	0.021	6.23	1.48
SE Pac.	-0.0539	-0.787	1.42

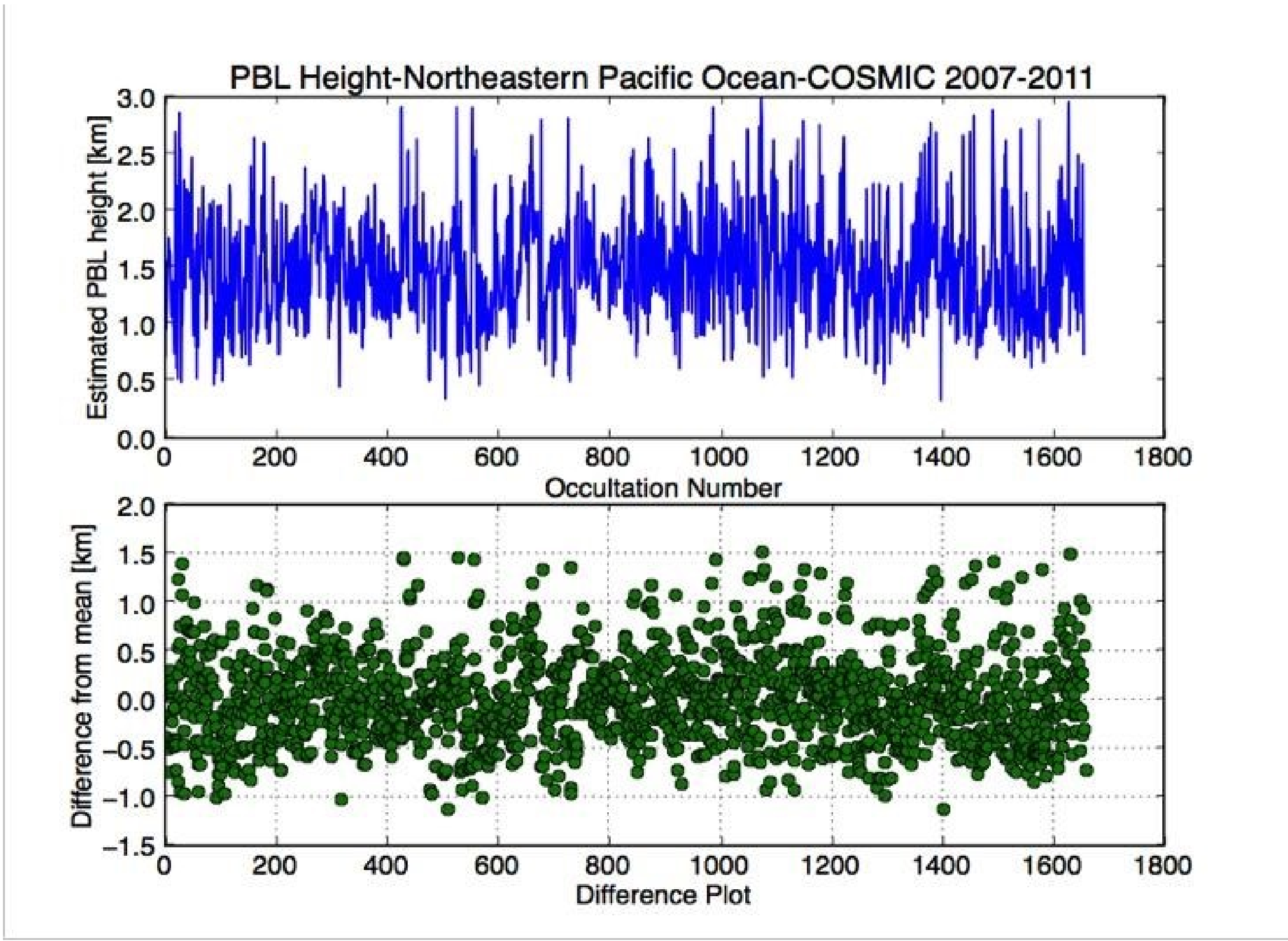

Figure 2. Full Occultation Data Set: Northeast Pacific Ocean. COSMIC data from 2007-2011 was analyzed via application of the PBL-depth determining algorithm. The seasonal cycles are somewhat visible, however, difficult to quantify due to high levels of noise.

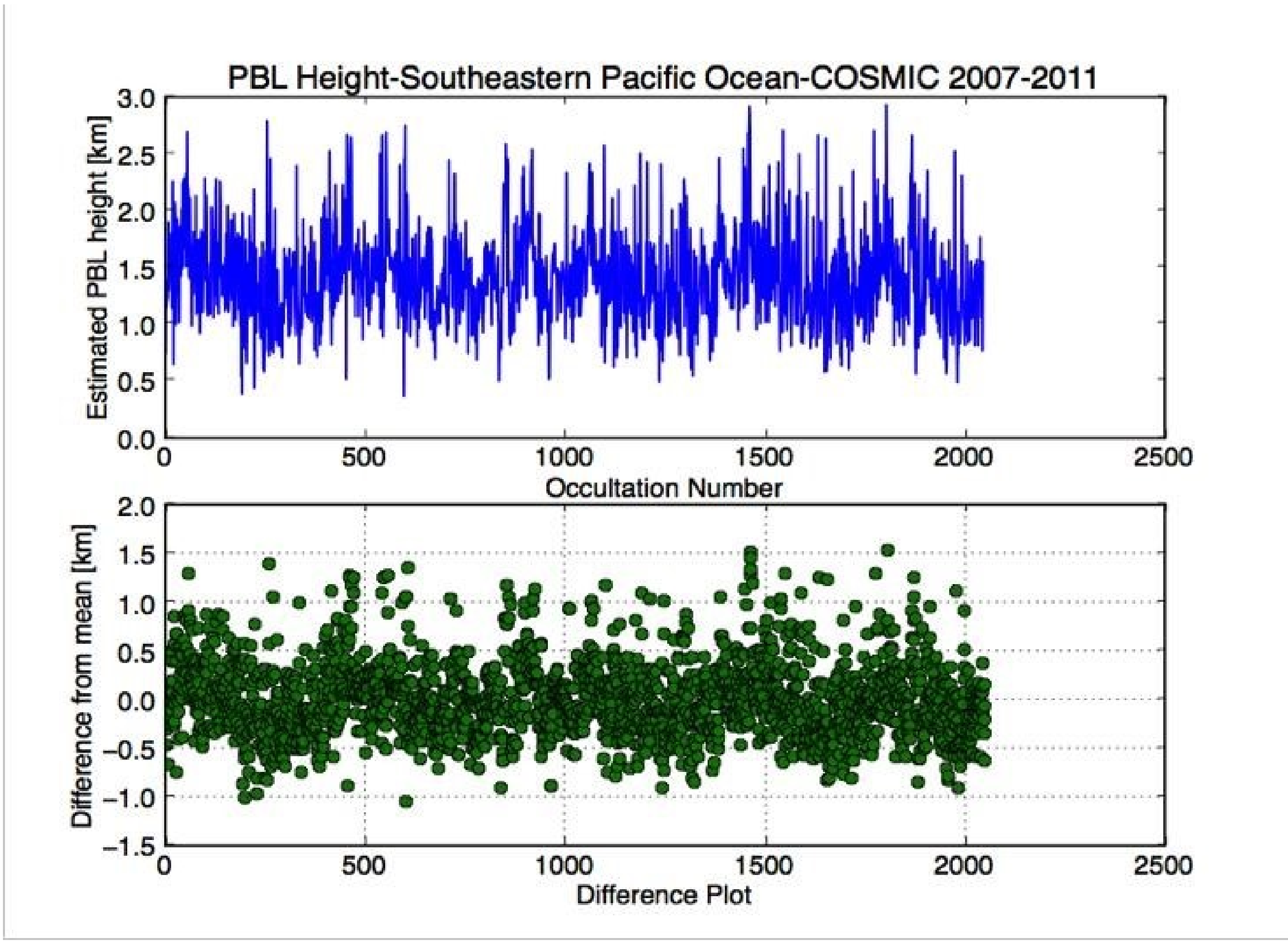

Figure 3. Full Occultation Data Set: Southeast Pacific Ocean. Base analysis of Southeast Pacific data was performed by simply applying the PBL-top determining algorithm to each individual profile in the set. Semblances of periodicity are observable.

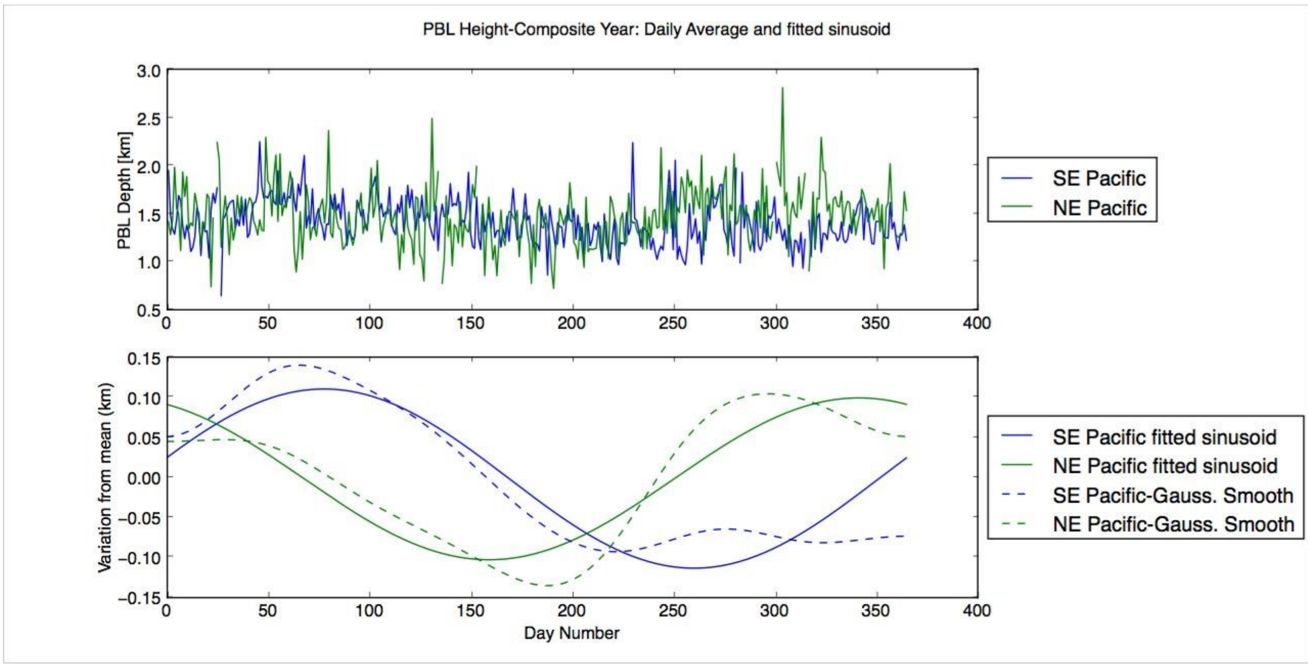

Figure 4. Seasonal Variability. Seasonal Variation was analyzed by fitting sinusoids and using a one-dimensional Gaussian Filter.

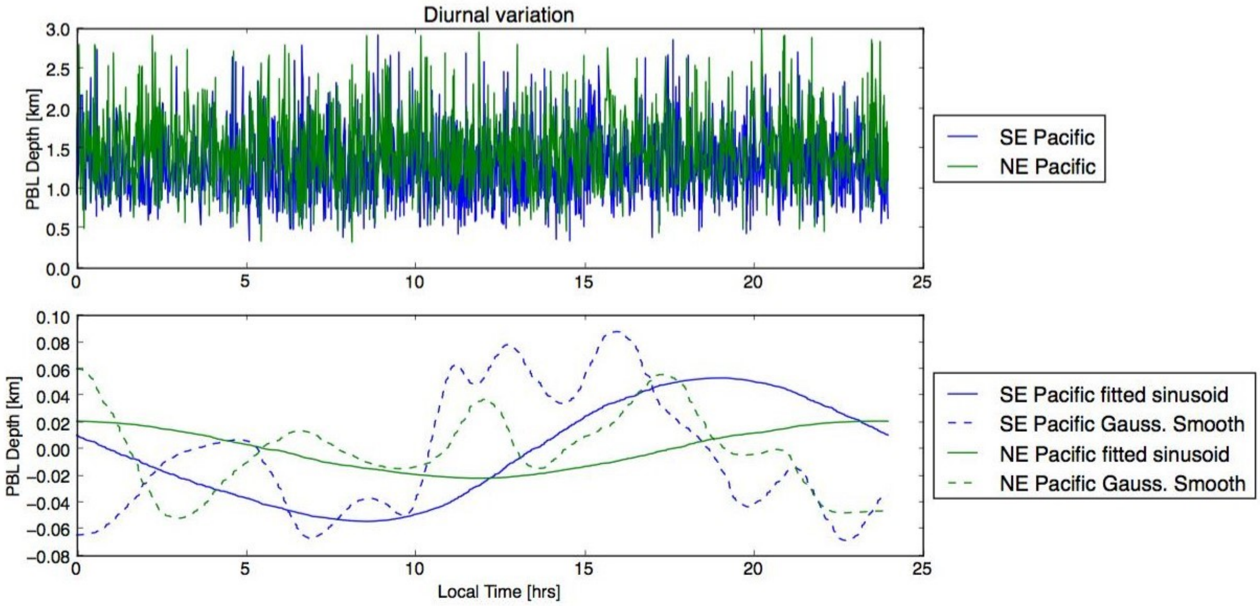

Figure 5. Diurnal Variability. Diurnal Variation was analyzed by fitting sinusoids and using a Gaussian filter

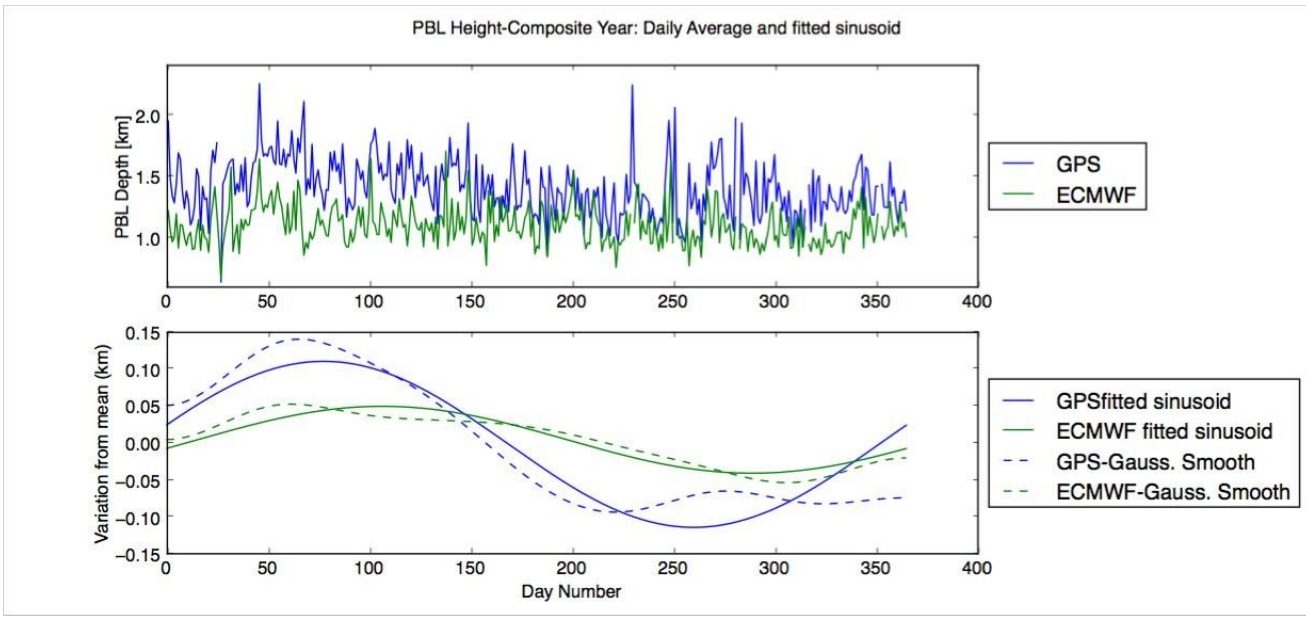

Figure 6. SE Pacific ECMWF- Composite Year. Seasonal Variation was analyzed by fitting sinusoids and using a one-dimensional Gaussian Filter.

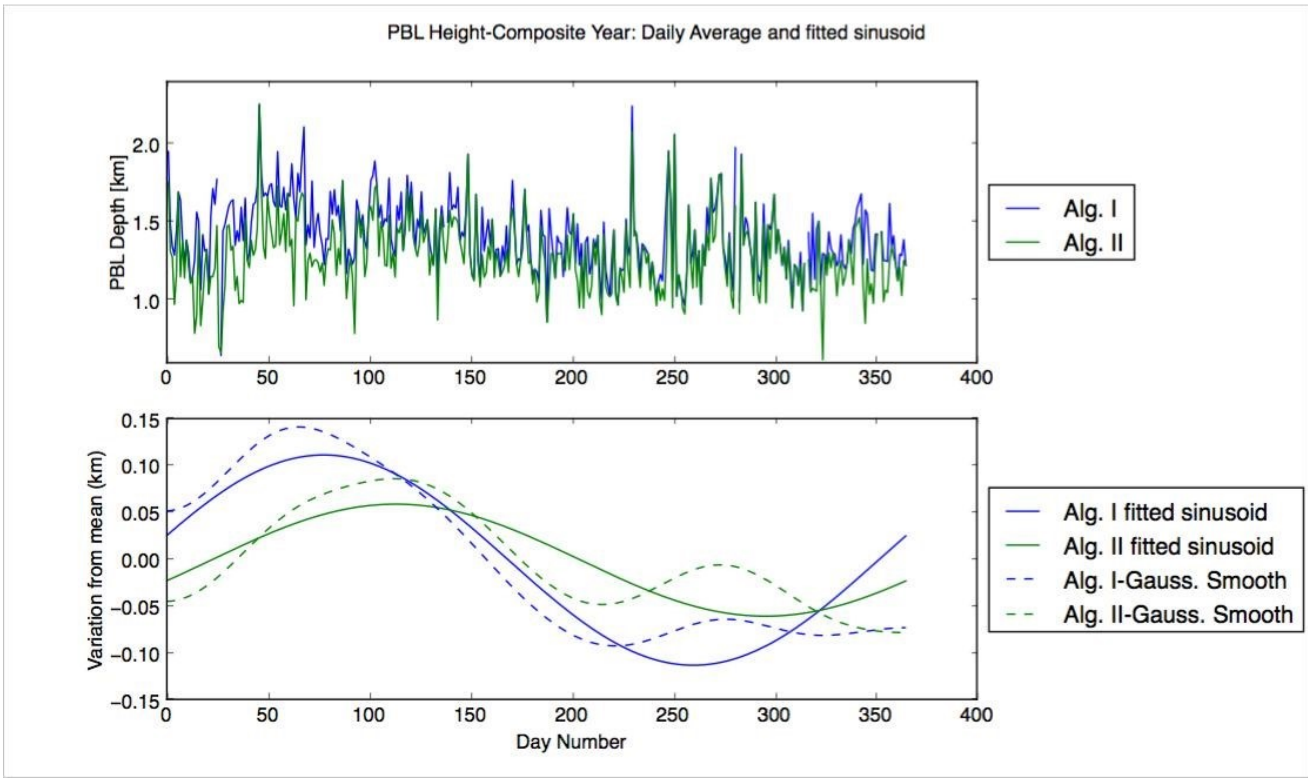

Figure 7. Comparison of Algorithms. A second, slightly modified algorithm was used that favored lower PBL heights.