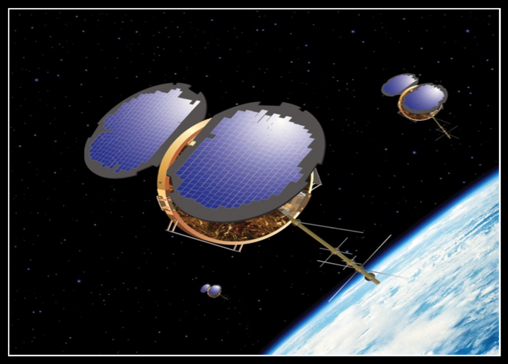


Remote Sensing of the Thermal Structure of Marine Boundary Clouds in the Southeast Pacific using COSMIC, CALIOP, and Radiosonde Data

Shu-peng Ho[1], Liang Peng[1], and Ying-Hwa Kuo[1,2]

1. University Corporation for Atmospheric Research/COSMIC, USA

2. National Center of Atmospheric Research, UCAR

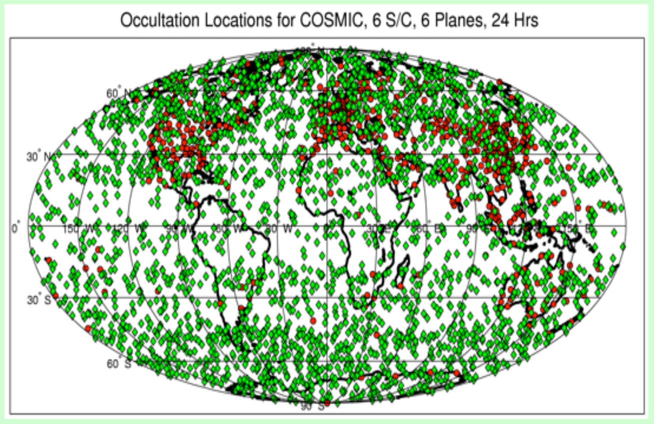
Corresponding author address : Dr. Shu-Peng Ho, COSMIC, UCAR, PO BOX 3000 Boulder, Colorado, 80307-3000. E-mail address: spho@ucar.edu, Tel: (303)497-2922

1. Introduction

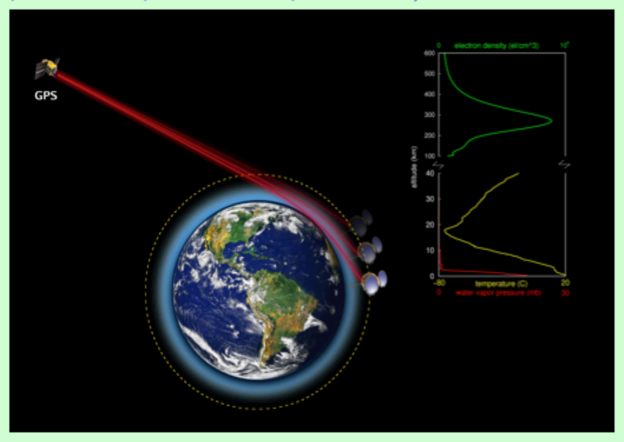
Accurate characterization of the evolution of the planetary boundary layer (PBL) height is critical to quantify the exchange of energy and moisture from the Earth surface to the free troposphere, which in turn impacts the formation of clouds and water and energy cycles. Recent studies have shown that the high vertical resolution Global Positioning System (GPS) radio occultation (RO) data from FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) are very useful to detect the PBL heights. However, due to lack of high vertical resolution in situ observations, validation of RO PBL height especially over the oceans is very difficult. **In this study, the PBL heights derived from COSMIC RO data are compared to those derived from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) measurements over ocean where wide spread persistent** marine boundary layer (MBL) stratocumulus clouds occurred. Over these regions, the MBL cloud top height is usually well defined by the marine boundary layer height (MBLH).

Characteristics of GPS RO Data

- **Measure of time delay: no calibration is needed**
- **High precision (<0.05K) (Ho et al., TAO, 2009a; Ho et al., JGR, 2009b, 2012)**
- **Insensitive to clouds and precipitation (vertical resolution ~ 60 meter)**
- **Detection of cloud top height using RO data (Biondi et al., 2012 ACP; Biondi et al., 2013 JGR)**



Typical distribution of COSMIC GPS radio occultation soundings (green dots) over a 24-h period over the global. Red dots are distribution of operational radiosonde stations.



By placing a receiver on board a low Earth orbiting satellite, we can measure the bending of radio signals transmitted by GPS satellites as they set or rise behind the Earth.

2. MBL height detection using COSMIC RO Data over the Southwest Pacific during the VOCALS-Rex

In this study, COSMIC bending angle, refractivity, and water vapor pressure profiles are used to derive the MBL height. In a neutral atmosphere the refractivity (*N*) is related to pressure (*P* in mbar), temperature (*T* in K) and water vapor pressure (in mbar) according to the following equation

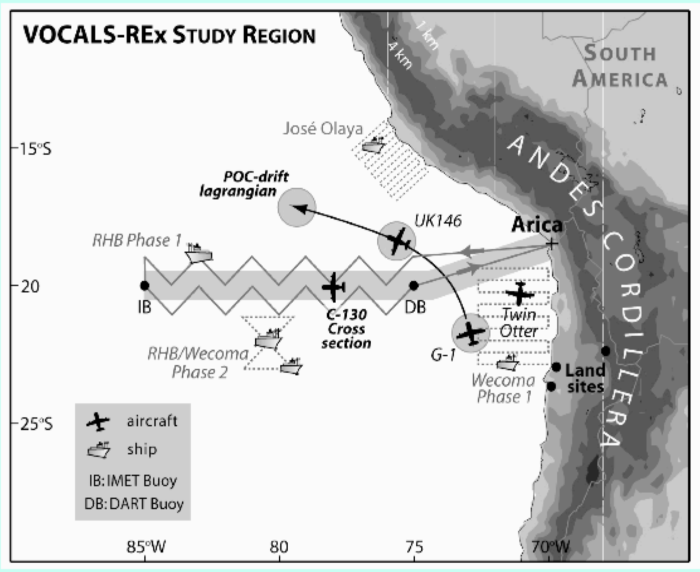
$$N = 77.6\frac{P}{T} + 3.73\times10^{5}\frac{P_W}{T^2}$$

1) Minimum Gradient method (MG)

$$X'(Z_i) = \frac{X(Z_i) - X(Z_{i-1})}{Z_i - Z_{i-1}}$$

2) Break Point (BP) method: Sokolovskiy et al. [2006] And Guo et al., [2011] estimated the MBL height by finding the "break point" in the N profile. This is an approximation of the second derivative of the N profile and is the so-called "break point" in the profile.

The spatial and temporal variability of the MBL over The Southeast Pacific is studied using radiosonde data from the VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx) are quantified.



VOCAL-REx: the MBL cloud top height is usually well defined by the marine boundary layer height (MBLH).

3. Collocation of CALIPO and COSMIC data

CALIPO data: onboard Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, CALIOP is a two-wavelength (532 nm and 1064 nm) polarization-sensitive lidar that provides high-resolution vertical profiles of aerosols and clouds (from September 2007 to March 2010).

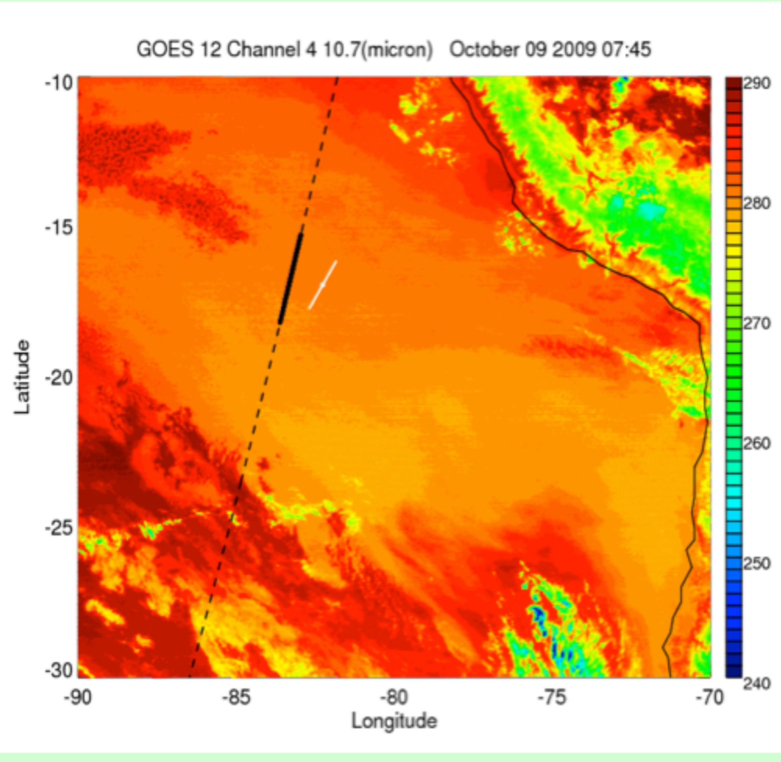
Collocation criteria :

1) within the 200-km and 2-hour window,

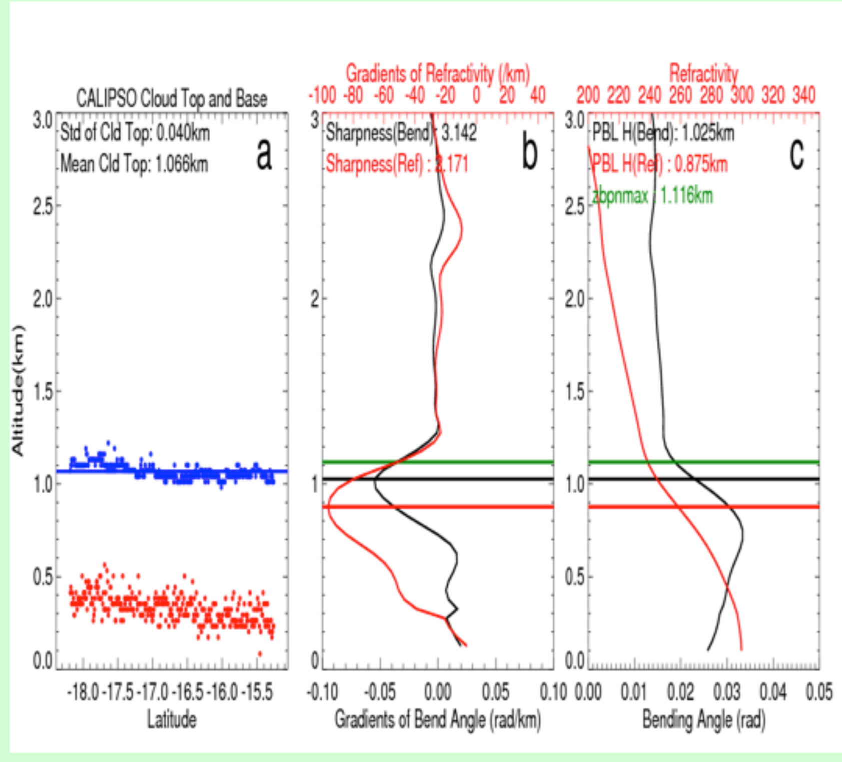
2) more than 150 CALIOP pixels,

3) CALIOP ensemble relative to its mean is less than 0.1 km are used.

This is to reduce the possible cloud heterogeneity (i.e., broken clouds) for RO-CALIOP pairs.



The CALIOP track (dashed black line) within the 200-km and 2-hour window (in a heavy black line) together with the RO track (white line) and the tangent point of the RO at 08:34 UTC Oct. 9, 2009 (center of white line). The tracks are plotted on a GOES image of the 10 μm window channel (indicating the cloud top temperatures)

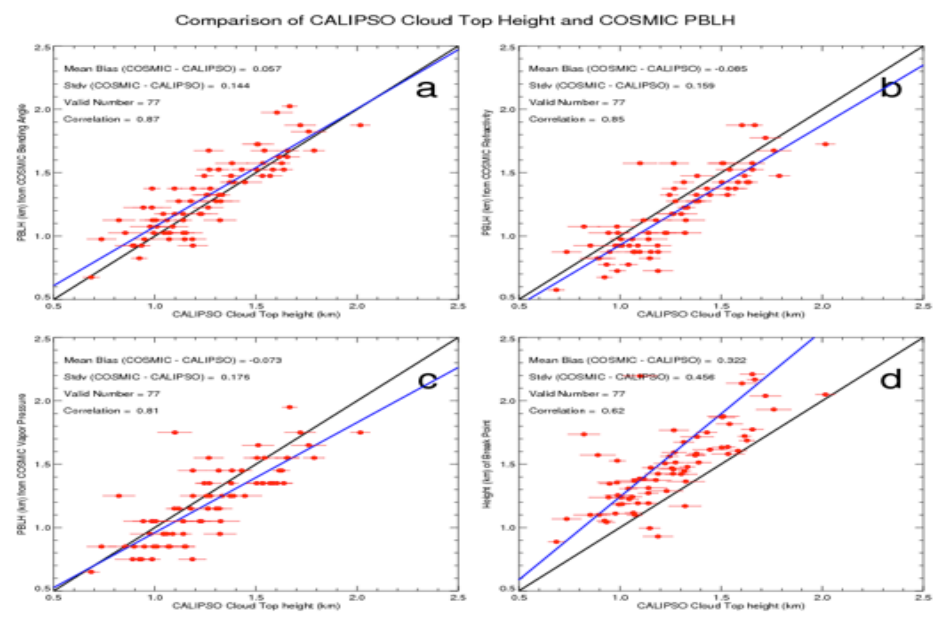


The cloud top and base heights from CALIOP are also shown in the left panel. The MBLH derived from the bending angle (black line) and refractivity (red line) using the MG method.

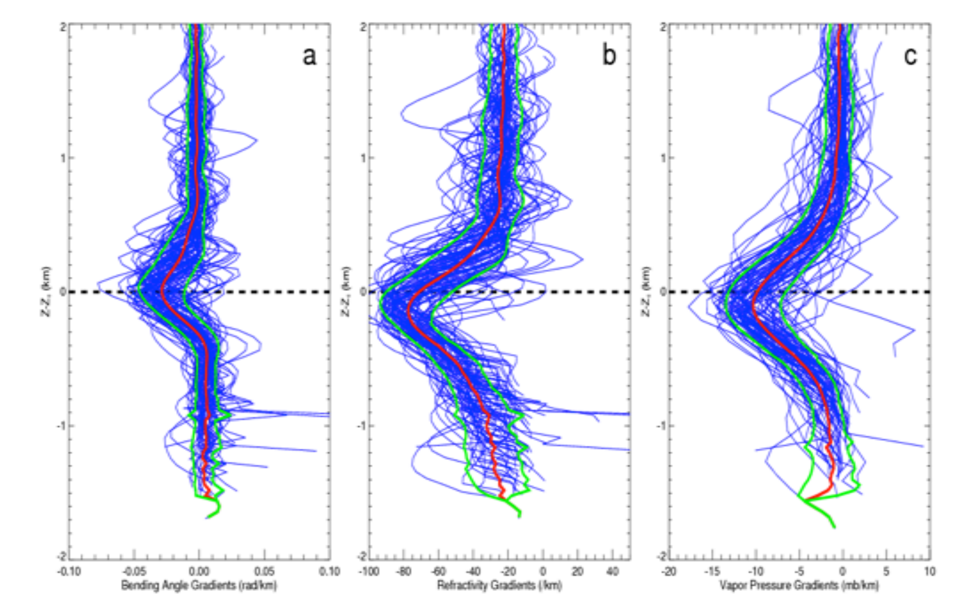
4. Statistical comparisons of MBLH from COSMIC and co-located CALIOP Cloud-top Observations

Figure on the left depicts the scatter plots for all the 77 RO-CALIOP pairs for $MBLH_{BA}$, $MBLH_N$, $MBLH_{wv}$, and $MBLH_N$ using breaking point method with the corresponding CALIOP MBLH, respectively. In general, the RO-defined MBL heights from bending angles, refractivity, and water vapor pressure are more similar to the CALIOP cloud tops than are the heights estimated from the Break Points in refractivity. The mean differences for $MBLH_{BA}$, $MBLH_N$, $MBLH_{wv}$, and the heights estimated from the Break Points in refractivity relative to the are equal to 0.06 km, -0.09 km, -0.07 km, and 0.3 km, respectively.

Figure on the right depicts the vertical distribution of bending angle gradient, refractivity gradient, and water vapor pressure gradient with the respect to the altitude of the corresponding CALIOP cloud top heights.



The scattering plot for COSMIC MBLH for (a) $MBLH_{BA}$, (b) $MBLH_N$, (c) $MBLH_{wv}$, and (d) $MBLH_N$ using breaking point method with the corresponding CALIOP MBLH, respectively

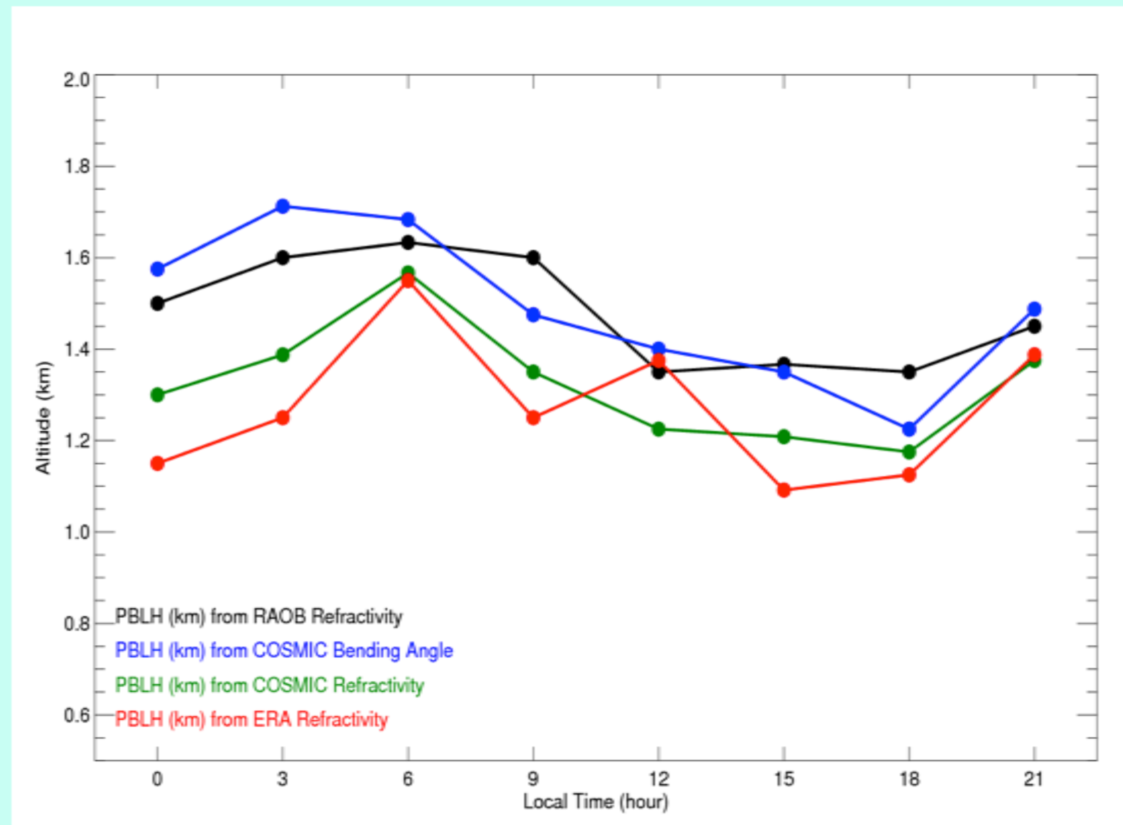


The vertical distribution of bending angle gradient, refractivity gradient, and water vapor pressure gradient with the respect to the altitude of the corresponding CALIOP cloud top heights.

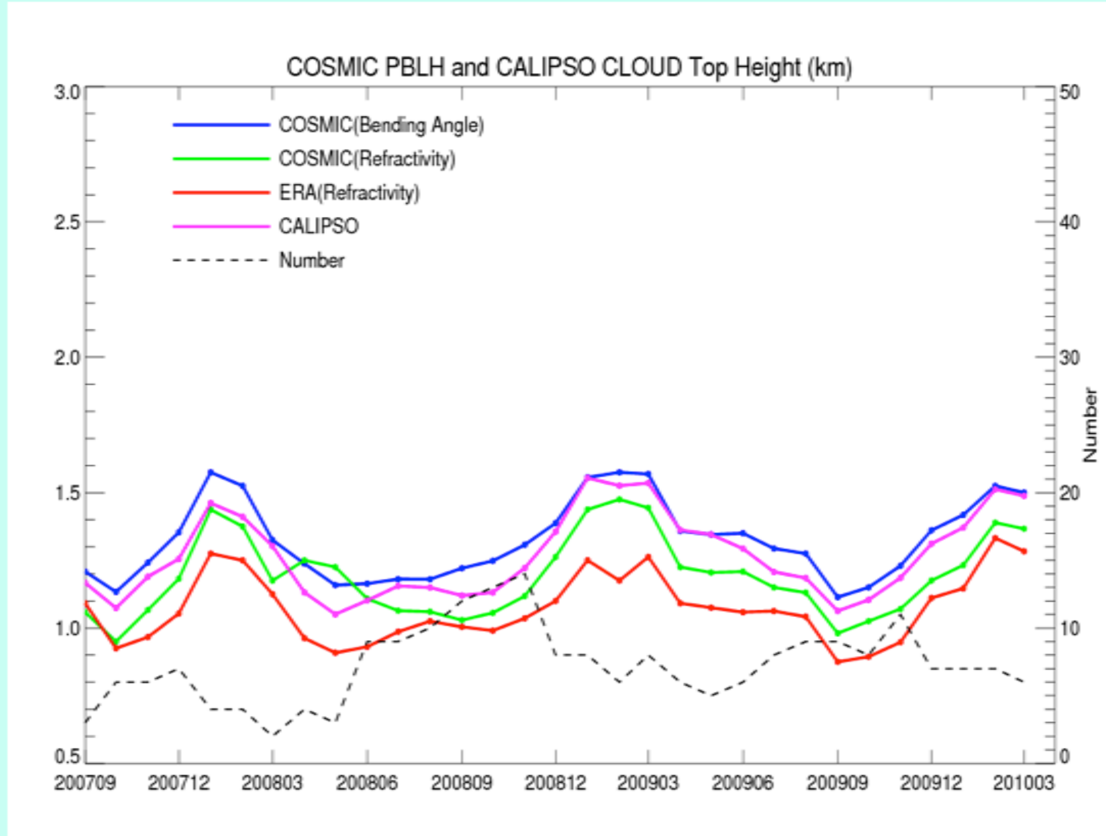
5. Diurnal and Inter-annual MBLH Variations

Figure on the left depicts the diurnal variation of the binned $MBLH_{BA}$ and $MBLH_N$ with that from co-located $MBLH_{RAOB}$. The $MBLH_{WV}$ derived from ERA-Interim refractivity profiles in the time and location of the COSMIC data are also compared.

Figure on the right depicts the seasonal variation of the RO MBLH and those from CALIOP. Three month running means from September 2007 to March 2010 are plotted. For each month, the $MBLH_{BA}$ is slightly higher than where $MBLH_N$ is slightly lower. Both $MBLH_{BA}$ and $MBLH_N$ follow the seasonal variation of very well.



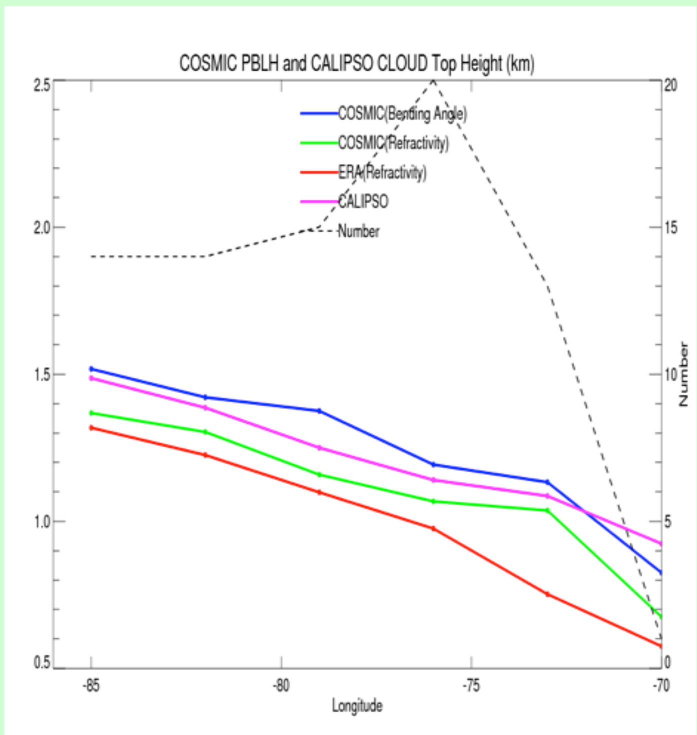
The diurnal variation of the binned $MBLH_{BA}$ and $MBLH_N$ with that from co-located $MBLH_{RAOB}$.



The seasonal variation of the RO MBLH and those from CALIOP from September 2007 to March 2010.

6. Conclusions

- **The spatial and temporal variability of the marine boundary layer height (MBLH) over the Southeast Pacific is studied using radio occultation data from the COSMIC satellites, lidar cloud measurements from the CALIOP instrument on the CALIPSO satellite, and the ERA-Interim reanalysis from September 2007 to March 2010 over the VAMOS Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx).**
- **The comparison results show that for regions that are dominated by the persistent marine boundary layer clouds, the planetary boundary height is very well defined by the MBLH. Although COSMIC variables are not sensitive to clouds, they are very sensitive to vertical density variation, which depend on temperature, pressure, and water vapor profiles associated with clouds. The sharpest gradient change for BA, N, and WV occurs at the similar height of CALIPO cloud top height.**
- **The mean MBLH differences among $MBLH_{BA}$, $MBLH_N$, and $MBLH_{WV}$ are within 0.15 km. The mean differences for $MBLH_{BA}$, $MBLH_N$, $MBLH_{WV}$, and relative to the are equal to 0.06 km, -0.09 km, and -0.07 km, and 0.3 km, respectively and their corresponding correlation coefficients are equal to 0.87, 0.85, 0.81, and 0.62, respectively.**



The mean longitudinal variation of RO derived MBLH in the VOCALS-Rex region is shown. This shows that the $MBLH_{BA}$, $MBLH_N$, and MBLH from CALIOP increase from around 1 km near 70º W to 1.5 km at 86º W.

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