

## Using CHAMP radio occultation data to determine the top altitude of the Planetary Boundary Layer

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### Abstract.

A simple approach to derive the Planetary Boundary Layer (PBL) top altitude from CHAMP (CHALLENGING Minisatellite Payload) radio occultation (RO) data is presented. Our RO processing cuts off at an altitude, typically  $\leq 4$  km, below which the GPS signals are affected by tracking errors. This lowest processed altitude (LPA) is assumed to coincide with the PBL top. We average LPAs for the years 2001 to 2004 over 5 Degree latitude longitude boxes and compare them to ECMWF analysis data. The ECMWF PBL top was calculated from the relative humidity gradient with respect to altitude. Agreement between the datasets is good in terms of mean PBL height, especially over sea. The CHAMP data shows the major features of PBL height with a realistic transition from stratocumulus regions to shallow and deep cumulus areas. CHAMP also shows a substantial amount of PBL height variability that may prove useful to study PBL dynamics.

### 1. Introduction

Since the 1850s when C. Piazz-Smyth found the trade-wind inversion by measuring the temperature when climbing the peaks of Tenerife (Canary Islands), the trade-wind inversion has been the center of many research efforts in tropical and sub-tropical meteorology. Several campaigns followed these first measurements. The work of *von Ficker* [1936] has helped to establish the trade-wind inversion as an ubiquitous part of the Hadley circulation and the tropical climate.

Recently scientists have become aware of just how important the dynamics of PBL inversions is to the overall climate system, e.g. [Ma *et al.*, 1996; Philander *et al.*, 1996]. The sub-tropics are the regions of the globe where persistent sheets of Stratocumulus (Sc) clouds cool the planet by reflecting a substantial portion of the downwelling shortwave radiation. In fact, the regions of the world where the cloud radiative forcing is largest are the ones associated with Sc off the west coasts of continents. The amount of clouds in the sub-tropics is highly correlated with the depth of the PBL (the height of the PBL inversion). Shallower boundary layers are associated with larger cloud cover due to a moister (in terms of relative humidity) PBL. Deeper boundary layers are associated with trade-wind cumulus and smaller values of cloud cover.

How the transition from shallower PBLs with Sc to deeper PBLs with cumulus happens, and what physical mechanisms are involved is still a matter of research, although significant progress has been achieved during the last twenty years. Much of this progress has been achieved through a successful combination of theory and intensive observational campaigns in the sub-tropics (ASTEX, FIRE, DYCOMS, see e.g. [Ackerman *et al.*, 2004]). But unfortunately, these experiments are always localized in space and time and do not provide a realistic global picture of the PBL inversion or cloud cover.

Satellite remote sensing in the visible and infrared has been relatively successful in measuring variables associated with clouds. However, direct measurements of the PBL inversion characteristics have been difficult to achieve mainly due to limited vertical resolution. Although recently some progress has been made using AIRS data to study PBL inversions [Fetzer *et al.*, 2004] and MODIS and TRMM data to derive the PBL depth in selected regions [Wood and Bretherton, 2004].

Radio occultation (RO) offers a promising alternative for global PBL inversion measurements. A RO instrument is usually located on a low earth orbiting satellite and observes the Global Positioning System (GPS) satellites in limb. The varying density (refractivity) profile of the neutral atmosphere will cause the GPS signals to be refracted (bent) from a straight line. The bending magnitude depends mainly on the atmospheric vertical refractivity gradient, which depends on temperature and water vapor. Consequently, RO allows the determination of temperature and at lower altitudes also the water vapor profile [Kursinski *et al.*, 1997; Rocken *et al.*,

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1997].

Probing of the PBL using RO instruments has already been discussed in the scientific literature, e.g. *Hajj et al.* [2004] discuss to use the signal reappearance after entering the PBL. Here, we derive the PBL height by correlating it with the Full Spectrum Inversion (FSI) [*Jensen et al.*, 2003] amplitude. We analyze results by comparing them to the PBL height as obtained from the European Centre for Medium-range Weather Forecasts (ECMWF) operational daily analysis.

From some previous studies it is now relatively well established that the ECMWF model and analysis are able to reproduce the height of the boundary layer over the ocean in a realistic way. Comparisons with radiosondes are for example published in *von Engel et al.* [2003]; *von Engel and Teixeira* [2004], they show that ECMWF's simulations of PBL height compare well with radiosonde data. Studies that focused on the stratocumulus regions, where strong inversions are detected above the PBL, have also shown the quality of ECMWF's predictions of the PBL height [*Duynkerke and Teixeira*, 2001]. As mentioned above however, there are not many ways of validating the accuracy of PBL height forecasts from weather prediction models. The method that we are proposing in this paper can thus prove itself to be an important tool to study and evaluate the forecasts of PBL height from ECMWF and other models.

## 2. Data Processing

The FSI is used to process CHAMP data at the GeoForschungsZentrum Potsdam, Germany. Processing stops when the smoothed occultation FSI amplitude is reduced by 50%. This is also used for the operational data stream, although several quality control measures lead to slightly higher mean altitudes. In total there are about 175,000 CHAMP occultations for the years 2001 to 2004 [*Wickert et al.*, 2005].

The ECMWF global analysis data covers the CHAMP observation period for the years 2001 to 2004, with a 1.5° resolution and 60 vertical levels (about 18 levels between 0 km and 3 km). ECMWF fields show generally good agreement with the PBL altitude from radiosonde data, as mentioned above. The top of the PBL in the ECMWF dataset was derived by finding at each gridpoint the altitude where the decrease of relative humidity with height is largest, under the constraint that the temperature is above 273 K. This approach is a typical one for the determination of the subtropical PBL top.

## 3. PBL Top and CHAMP Altitude

ECMWF atmospheric profiles have first been used in a RO simulator to verify the sensitivity of the CHAMP receiver to the PBL top. The simulator has already been successfully run to study the negative refractivity bias in CHAMP observations [*Beyerle et al.*, 2003, 2004]; here we use CHAMP-like receiver tracking errors as found in the

tropics.

In total, 500 ECMWF profiles have been selected, the atmosphere was assumed to be spherical symmetric. Profiles were randomly chosen with respect to time and location near the track shown in Figure 1 (top). Only ocean based locations were chosen with a 10 Degree random variation in longitude and latitude along this track. This particular area is selected since it represents the climatology of a typical transition from Sc, to cumulus and then to deep convection. The indicated track has also been used in intercomparison studies of atmospheric model parameterizations [*Siebesma et al.*, 2004].

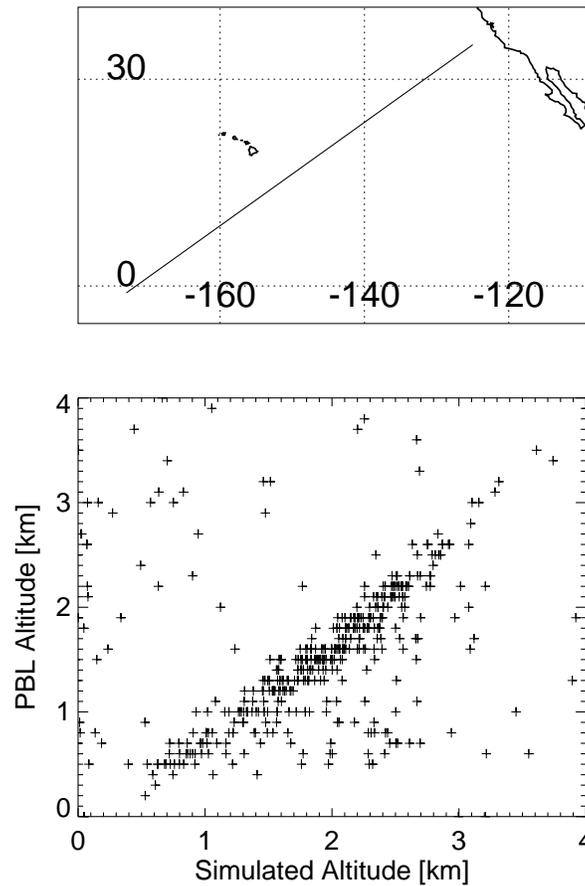
Although there is no requirement for a distinguished PBL top in the ECMWF profile, Figure 1 (bottom) shows that the majority of the simulations terminate slightly above the PBL altitude, indicating that the FSI amplitude cutoff is slightly too high. A maximum altitude of about 3 km can be identified, the few cases above do not show such a clear correlation; the decreasing altitude resolution of the ECMWF data is not able to capture the PBL inversion above [*von Engel and Teixeira*, 2004]. Cases where the simulated altitude is well below (above) the PBL top are probably caused by very weak inversions (double peaks in the relative humidity gradient).

Note that the presented results depend on the tracking algorithm used onboard the receiver. Software updates to the tracking algorithm will modify the relation of the PBL top altitude to the 50% FSI amplitude one. In particular the open loop implementation will probe more frequently into the PBL [*Sokolovskiy*, 2001], thus allowing more advanced techniques for probing the PBL such as direct observation of spikes in the bending angles or a temporary drop in the FSI amplitude.

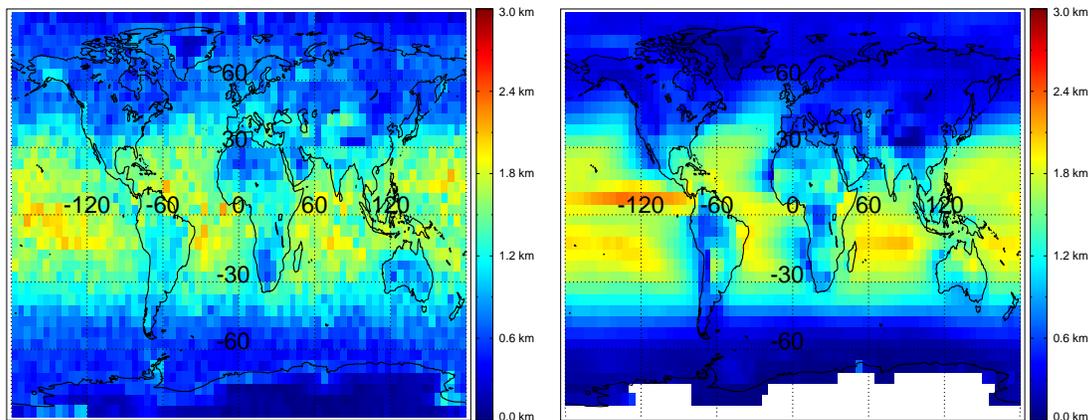
## 4. Results

A comparison of CHAMP and ECMWF mean PBL altitudes above the Earth surface is shown in Figure 2. Based on the simulations shown above, all occultations terminating above 3 km were removed (about 33,000). 142,347 occultations were left (53,815 over land). On average, almost 55 measurements enter each grid box, although this is latitude dependent; about 38 profiles (62) enter at tropical (mid) latitudes.

Both plots show similar features, especially over the Ocean. Mean altitudes around 0 km are found for polar latitudes. Also visible is the gradual increase in PBL height when moving from polar latitudes toward the equator. Over the sub-tropics and tropics, the transition from a relatively shallow PBL with Sc close to the west coasts, to a deeper PBL with cumulus [*Duynkerke et al.*, 1999; *Stevens et al.*, 2001; *Siebesma et al.*, 2003], is visible in both datasets. Although it is clear that in the Sc regions ECMWF gives values that are consistently lower. In the deep tropics the two datasets diverge in some regions: 1. In the Eastern Pacific, around 10 N, the ECMWF data shows a peak value for the



**Figure 1.** Top: Track along which a random selection of ECMWF profiles were chosen. Bottom: PBL height versus lowest altitude reached in simulator.



**Figure 2.** Left: Mean minimum altitude found in CHAMP data. Right: Mean altitude of minimum relative humidity gradient calculated from corresponding ECMWF data. Data is averaged over a  $5^\circ$  latitude longitude grid. Altitudes are with respect to the ground. White areas indicate temperatures always below 273 K.

PBL height that presumably corresponds to the inter-tropical convergence zone (ITCZ); 2. In the Western Pacific, a maximum is apparent in CHAMP at around 10–15 N.

Although there are differences between CHAMP and ECMWF, the sub-tropical PBL evolution is captured relatively well by the CHAMP data. For example the transition in PBL height from the coast of California to Hawaii and the equator is relatively similar in both datasets; Figure 3 shows the mean PBL height cross-section along the track given in Figure 1 (top). A PBL increase in both data sets from about 1 km at 30 N, to about 2 km south of 15 N is found. Also, both datasets show a PBL height around 2 km in the tropics. The higher ITCZ altitudes of ECMWF are found at 10 N. Close to the coast the two data sets diverge a little, possibly due to topography issues. Also shown in Figure 3 is the relatively large standard deviation (around 1 km) of the CHAMP data set.

## 5. Conclusion

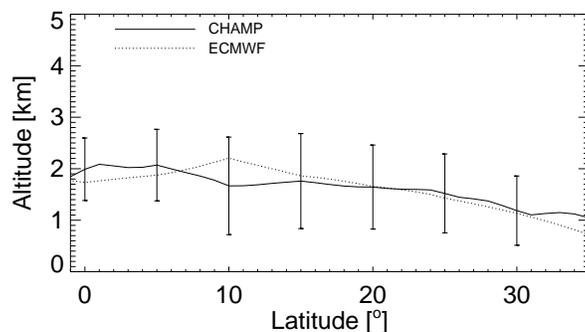
We use FSI processed CHAMP RO data for the years 2001 to 2004 to estimate PBL heights. A simple approach was used by assuming that the altitude where the FSI amplitude has dropped by 50 % coincides with the PBL top, as verified by simulations. This altitude is compared to ECMWF analysis data for the same period. The ECMWF PBL top is calculated as the altitude where the gradient of relative humidity with respect to height shows its minimum. Maps of mean PBL height show good agreement between CHAMP and ECMWF, in particular over the Ocean. The transition in mean PBL height from the Sc regions to the cumulus and deep cumulus areas is well captured by the CHAMP data. Moreover, the CHAMP data exhibits a fair amount of variability in PBL height. Although this variability looks reasonable it is still unclear how much of it is actually representing the dynamics of the PBL height.

This and other issues will need to be investigated further in order to precisely define the usefulness of the CHAMP data set as an instrument to understand the dynamics of the PBL height in a global perspective. Future work will focus on more sophisticated algorithms to derive the PBL height from RO data and on how to use the amplitude to derive further information such as inversion depth. Also, tracking software updates of the receiver will require the development of modified algorithms. It is anticipated that this data could be assimilated into weather prediction models.

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**Figure 3.** Latitude longitude slice of the mean PBL altitude from CHAMP data over a  $5^\circ$  latitude longitude grid. Vertical lines indicate the error bars. Also shown is the PBL top altitude in the corresponding ECMWF data.

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