Monitoring the Atmospheric Boundary Layer (ABL) by Radio Occultation Signals Recorded by COSMIC Satellites

S. Sokolovskiy, Y.-H. Kuo, C. Rocken, W. Schreiner, D. Hunt, R. Anthes and D. Lenschow

University Corporation for Atmospheric Research
National Center for Atmospheric Research

AGU Fall Meeting, San-Francisco, December 11-15, 2006
Abstract

The Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) uses radio occultation (RO) observations of the Global Positioning System (GPS) satellites to retrieve vertical profiles of the bending angle and refractivity in the atmosphere. Unlike previous RO missions utilizing the phase-locked loop (PLL) signal tracking technique, COSMIC receivers record L1 GPS signals in open-loop (OL) mode in the lowest 10 km of the troposphere by allowing penetration of the retrieved profiles down to the ocean surface. This provides an opportunity for monitoring the atmospheric boundary layer (ABL) with high vertical resolution (50-100 m), not available from other satellite data and not generally possible with PLL RO data from previous RO missions due to insufficient penetration and tracking errors. The optimal way of utilizing information about the ABL from RO observations is direct assimilation of the inverted bending angle and refractivity profiles into atmospheric models with sufficiently high vertical resolution in the lower troposphere. Alternatively, estimates of the depth of the ABL, which is an important parameter for meteorology and climatology, can be extracted from the structure of RO signals and inverted profiles.
FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate)

- 6 Satellites launched
  01:40 UTC 15 April 2006
- Three instruments:
  - GPS receiver, TIP, Tri-band beacon
- Weather + Space Weather data
- Global observations of:
  - Pressure, Temperature, Humidity
  - Refractivity
  - Ionospheric Electron Density
  - Ionospheric Scintillation
- Demonstrate quasi-operational GPS limb sounding with global coverage in near-real time
- Climate Monitoring
FORMOSAT-3/COSMIC - Final Deployment

- 71 Degrees inclination
- 800 Km
- 2500 Soundings per day
- 6 Planes
- Latency 50-140 minutes from observation to NOAA
Global coverage - 2500 Daily Soundings by early 2007

- Red - Daily average Radiosondes
- Green - Daily COSMIC Soundings
With the open-loop tracking, by accurate modeling of the frequency and range in receiver, the RO signals are recorded deeper than with the closed-loop tracking.

This results in:

(i) better penetration of retrieved profiles (especially in tropics); over oceans, most of open-loop profiles penetrate close to $z=0$; closed-loop profiles, commonly do not penetrate in layers with sharp vertical $N$-gradients

(ii) smaller negative $N$-bias in tropical lower troposphere

(iii) larger standard deviation of retrieved $N$ profiles in the troposphere from those reproduced by atmospheric models; this is explained by insufficient vertical resolution of the atmospheric models (in closed-loop, only RO signals corresponding to vertically smooth $N$-profiles are tracked deep enough; in open-loop all RO signals are tracked and all $N$-profiles are equally represented in statistics)
Statistical comparison with ECMWF analyses

**CHAMP**

**COSMIC**

Global

Tropics
Examples of RO retrieved N profiles and AVN forecast in tropical troposphere
Diffraction by complicated vertical N-structures in moist tropical troposphere results in propagation of RO signals deep in GO shadow zone. Information content of RO signals in that zone is important for reconstruction of N-profiles.

If tropical RO signal is tracked insufficiently deep, this results in not only insufficient penetration, but also in inversion error above the FSI cutoff height.

Insufficient tracking depth results in inversion N-bias in moist tropical troposphere.

Reliable tracking of RO signals to any depth (height of straight line (HSL) between GPS and LEO), under low SNR, is possible with open-loop (with accurate modeling of the frequency and range preventing from loss of SNR).
Effect of tracking depth on inversions of tropical RO signals
Statistical comparison of COSMIC RO to ECMWF refractivities in tropics, for different tracking depths

-100km<HSL<-50km

-150km<HSL<-100km
Importance of Boundary-Layer Height

Here we define boundary-layer height as the depth to which turbulent mixing couples the atmosphere to processes at the Earth's surface on a time scale of a few hours or less. Thus it includes, for example, the fair-weather cumulus layer.

The Boundary Layer:
- Couples surface-based energy, momentum and trace constituent fluxes with the overlying atmosphere
- Determines the type and coverage of low-level clouds
- Determines air temperature and humidity close to the Earth's surface
How Can We Use Measurements of Boundary-Layer Height?

- A key parameter for modeling fair-weather cumuli and stratiform cloud cover
- Identify regions with a capping inversion (e.g. strong subsidence) and regions containing deep convection
- May delineate boundaries of cold upwelling ocean areas
- Useful as a tool for numerical climate and weather model verification
Diurnal evolution of the convective and stable boundary layers (BL) in response to surface heating (sunlight) and cooling. Over the ocean, the diurnal response is minimal, and the BL structure is similar to the daytime BL, typically varying in depth from about 500 to 1200 m.
Characterization I

Characterization of the top of turbulently mixed layer (ABL or cloud layer) by mean vertical gradients of refractivity and bending angle

\[
N = 77.6 \frac{P(mb)}{T(K)} + 3.73 \cdot 10^5 \frac{P_w(mb)}{T^2(K)}
\]

\[
\alpha = -2a \int_a^\infty \frac{d \ln n}{dx} \frac{dx}{\sqrt{x^2 - a^2}}
\]

\[
n = 1 + 10^{-6} N, \quad x = rn(r), \quad r = r_e + z
\]

\[a\quad \text{impact parameter}\]
An example of radiosonde profile in the presence of sharp ABL top at 2 km height.
An example of bending angle and refractivity profiles in the presence of sharp ABL top at 2 km altitude retrieved from COSMIC RO signal.

The height of maximum BA lapse in 0.3 km sliding window is estimated for each RO profile. Large BA lapse indicates top of ABL or cloud top.
ABL or cloud top height from COSMIC BA profiles day 260-273, 2006
(color scale shows height of max BA lapse >1E-2rad within 0.3 km)

MAP1

1303 Matches
Hurricane tracks 2006 (Jan-Sept)

In E-Pacific, W-Pacific & Mid-Atlantic, the regions where hurricanes start are correlated with the regions of low vertical N- & BA- gradients.
Characterization II

Characterization of the height of turbulently mixed layer by width of the sliding spectrogram of the FSI amplitude.

The Full Spectrum Inversion (FSI) transforms RO signal from time to impact parameter representation. In this representation, the amplitude is close to constant for spherically-symmetric refractivity $N(z)$. Deviation from spherical symmetry (turbulence) results in scintillation of the amplitude. The FSI amplitude is subject to the sliding-window spectral analysis. The width of the sliding spectrogram is estimated as function of impact height. The height where the spectral width substantially decreases indicates the top of turbulent (convective) layer.

Window 0.5 km.
Top height corresponds to the spectral widths $< 5 \text{ km}^{-1}$
Bending angle, FSI amplitude and width of the sliding spectrogram (0.5 km window) as functions of impact height in the presence of sharp top of ABL

C001.2006.240.05.45.G02 (22S, 90W)
Bending angle, FSI amplitude and width of the sliding spectrogram (0.5 km window) as functions of impact height in the absence of sharp top of ABL

Top height of convective layer from COSMIC FSI amplitude profiles (FSI amplitude spectral width < 5 km\(^{-1}\)) day 260-273, 2006
The inter-tropical convergence zone is characterized by the absence of sharp vertical gradients of BA (N, humidity) (MAP1).

The ABL (or cloud layer) is more shallow toward West coasts of America and Africa (MAP1). This indicates the upwelling zones.

Convection uprising to large altitudes ~8 km is observed in W. Pacific and Mid. Atlantic regions (MAP2) characterized by small mean vertical BA gradients (MAP1).

The hurricane tracks in E. Pacific, W. Pacific and Mid. Atlantic are correlated with the zones of low vertical BA gradients (MAP1). The hurricane tracks in W. Pacific are correlated with the zone of convection uprising to large heights (MAP2).
In addition to direct assimilation of RO retrieved BA and N profiles, RO signals recorded in open-loop mode provide two complementary techniques for monitoring moist tropical & sub-tropical troposphere:

1) Sharp vertical gradients of BA and N (associated with sharp gradients of humidity) can be used for estimation of the depth of ABL or cloud layer.

2) The high-frequency fluctuating structure of amplitude of RO signals transformed to impact parameter representation (FSI, CT) can be used for estimation of the depth of turbulently mixed (convective) layers.