Comparison of ABL Heights Derived from COSMIC RO and the RUC Model

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SOARS® Summer 2009

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ABSTRACT

This study investigates two approaches for determining the height of the Atmospheric Boundary Layer (ABL): analyzing radio occultation (RO) observations and using NOAA’s Rapid Update Cycle (RUC) model. The first approach determines the ABL height by examining radio wave bending angle profiles from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC). The second approach examines the vertical structure of meteorological parameters reproduced by the RUC model. This study compares the values of collocated ABL heights obtained by each approach over North America and adjacent oceans for both summer and winter months to determine seasonal variations. Significant differences in the ABL heights were found for the two approaches, as well as seasonal variations. High-precision comparisons were not produced between RUC and COSMIC ABL heights because this ABL analysis did not include RUC model data for water vapor and turbulence. To perform a better comparison, the RUC ABL should be better characterized by accounting for water vapor and turbulent mixing data.
Introduction

Different approaches have been explored to accurately determine the Atmospheric Boundary Layer (ABL) height. The ABL is the lowermost layer of the atmosphere. It is characterized by turbulent mixing generated by wind shear and convection, and it is directly affected by the earth’s surface on time scales of a few hours or less. The ABL is capped by a temperature inversion that separates it from the overlying stably stratified free atmosphere that is usually accompanied by a significant decrease of water vapor and relative humidity. It is valuable to determine the ABL height, for example, in forecasting the development or suppression of convective clouds. Further, observations of turbulent regions are useful for aircraft safety. Knowing the height and structure of the ABL and inversion layers is also useful for monitoring conditions of radio wave propagation. Moreover, the height of the transition layer, i.e., the height of the ABL, is an important variable for predicting essential climatic quantities such as global cloudiness, precipitation, and surface winds, and in many cases it is not well reproduced by atmospheric models.

This study investigates two approaches for determining the height of the ABL: Radio Occultation (RO) observations and using NOAA’s Rapid Update Cycle (RUC) model. We will obtain ABL height from satellite observations used by the Constellation Observing Systems Meteorology, Ionosphere and Climate (COSMIC) system and from RUC model runs to determine the strength of each approach.

As described in Anthes et al., (2007), one approach for observing and determining the height of the atmospheric boundary layer is demonstrated by using radio occultation data from the COSMIC mission. The six-satellite COSMIC mission was launched on April 15, 2006. This Low Earth Orbit (LEO) satellite system was primarily designed to produce GPS radio occultation observations of the neutral atmosphere and ionosphere. COSMIC instruments receive GPS radio signals from GPS satellites provided by the U.S. Department of Defense. It has emerged as a powerful and relatively inexpensive approach for sounding the global atmosphere with high precision, accuracy, and vertical resolution in all weather and over both land and ocean. After launch, the satellites were gradually deployed to their final orbits at 800 km, a process that took about 17 months. COSMIC radio occultation data are of better quality than those from previous missions and penetrate much farther down into the troposphere. With the ability to penetrate deep into the lower troposphere using an advanced open-loop tracking technique, the COSMIC radio occultation instruments can observe the structure of the tropical atmospheric boundary layer shown in Anthes et al., (2007). The value of radio occultation for climate monitoring and research is demonstrated by the precise and consistent observations between different instruments, platforms, and missions.

Each of the Low Earth Orbit (LEO) COSMIC satellites tracks the GPS satellites as they are occulted by the Earth’s limb. As a radio signal travels through the atmosphere, it is slowed and bent, causing phase and Doppler shifts that can be measured very accurately by the GPS receiver aboard the COSMIC satellites. Atmospheric and ionospheric profiles are derived from the measured phase and amplitude by use of inversion methods that include many processing steps.
including satellite orbit determination, bending angle calculation, and Abel inversion of bending angle into refractivity. In the neutral atmosphere, the bending angle-derived refractivity profiles are functions of temperature, pressure, and water vapor as described in Rocken et al., (2000).

Figure 1 shows how a COSMIC satellite moves relative to a GPS satellite to obtain a series of measurements through the ionosphere and atmosphere.

The first operational implementation of the Rapid Update Cycle (RUC) model occurred in 1994; there have been many advances since then. The RUC model is an operational mesoscale data assimilation and numerical forecast system run at NOAA’s National Center for Environmental Prediction (NCEP). It is designed to provide frequently updated numerical forecast guidance. The RUC runs at the highest frequency of any forecast model at NCEP, assimilating recent observations to provide hourly updates of current conditions (analyses) and short-range numerical forecasts. The RUC is unique among operational numerical weather prediction (NWP) systems in two primary respects: its hourly forward assimilation cycle and its use of a hybrid isentropic-terrain-following vertical coordinate for both its assimilation and forecast model components. The RUC model is also distinctive in its application at a much finer horizontal resolution (currently 10–20 km) than previous isentropic models. The RUC horizontal domain covers the contiguous 48 United States and adjacent areas of Canada, Mexico, and the Pacific and Atlantic Oceans with a 20-km grid.

The RUC model calculates terrain by using a slope envelope topography. The standard envelope topography is defined by adding the subgrid-scale terrain standard deviation (calculated from a 10-km terrain field) to the mean value over the grid box. By contrast, in the slope envelope topography, the terrain standard deviation is calculated with respect to a plane fit to the high-resolution topography within each grid box. This gives more accurate terrain values, especially in sloping areas at the edge of high-terrain regions. It also avoids a tendency of the standard envelope topography to project the edge of plateaus too far laterally onto lower-terrain regions. This feature will help us accurately calculate the ABL height from sea level.
We constructed a series of computer programs that extract ABL heights from COSMIC observations and the RUC model. Whenever radio occultation data revealed a well-defined ABL top, we extracted the ABL height from RUC model output interpolated to the time and location (latitude, longitude) of the RO, then compared it to the ABL height extracted from the RO. Our analyses from these comparisons allow us to determine the strength of each approach.

**Method**

To compare ABLs from COSM IC and RUC, we first isolate the latitude, longitude, and time coordinates for COSMIC RO measurements where a well-defined ABL top is evident. Then we derive the ABL height value for those same spatial and temporal coordinates from the RUC model. Finally we compare the COSMIC ABL heights to the matching ABL heights simulated by the RUC model. COSMIC determines the ABL height by detecting the decrease in refractivity that results from a significant decrease in humidity that often sharply defines the top of the ABL. The sharply defined ABL top results in a significant lapse of the bending angle $\Delta \alpha$ within small height interval $\Delta z$, as shown in Figure 2a. In the absence of a sharply defined top of the ABL, the bending angle profile $\alpha(z)$ does not have a single interval with large $\Delta \alpha$ but instead may be either smooth (Figure 2b) or have more or less statistically homogeneous fluctuation corresponding to moist convection, such as shown in Figure 2c. In COSMIC data, the top of the ABL is associated with the layer $\Delta z$ that corresponds to the maximum of the product of the bending angle lapse $\Delta \alpha$ and the bending angle gradient for a given RO profile, i.e., $\Delta \alpha^2 / \Delta z = \text{max}$ under the condition that $\Delta \alpha$ exceeds a certain threshold (Sokolovskiy et al., 2007). The choice of the threshold is subjective; it is based on the RO data analysis and trade-off between the number of selected occultations with sharp ABL top and the noisiness of these data.

Figure 2 shows bending angle profiles. (A) shows a profile with a sharp ABL top, (B) shows a smooth profile without a sharp top at all, and (C) shows a profile that does not have a significantly sharp ABL top but has fluctuation which may be due to multiple layers, convection, noise etc.
For this study we select occultations with $\Delta \alpha > 10^{-2}$ rad and the mean height of the layer $z < 3$ km. With these search criteria we find sharp ABL tops in RO data mainly in sub-tropics and mid-latitudes, but rarely find it in high latitudes (due to low humidity) and Intertropical Convergence Zone (due to strong convection uprising to large heights).

RUC acquires its ABL heights with a different method than COSMIC. In the RUC model, the ABL top is associated with the height where the virtual potential temperature decreases by 1 degree Celsius compared to its value at 1000 mb. This height is found for every model grid point and is provided as a scalar parameter in the grid model data. RUC uses a vertical profile of virtual potential temperature from RUC native levels, finds the height above surface at which theta-$\nu$ (virtual potential temperature) again exceeds theta-$\nu$ at the surface (lowest native level ~5 m above surface). As of a RUC upgrade on 17 November 2008, the surface theta-$\nu$ was boosted by an additional 0.5 Kelvin, which does not strongly affect the ABL height if it is already at least 100 m, but does avoid a diagnosis of zero height from a small (<0.5 K) inversion in the lowest 20 m (the vertical coordinate is height above surface in meters). This use of the RUC model calculates the ABL heights for us, and we just interpolate them to the locations of the RO measurements.

Figure 3 shows an example of virtual potential temperature. The temperature is constant as it goes up in height, then it changes. This temperature change in the RUC model indicates the ABL.

For comparison, we use the occultations satisfying the above criteria and interpolate the ABL heights from RUC grid fields to the locations (latitude, longitude) and time (UTC) of the occultations.

We constructed a series of computer programs that extract radio occultation profiles for each day in each month. One program checks the profiles to see if any meet the criteria for a sharply defined ABL top. If a profile meets the criteria, the program extracts the ABL height along with the latitude, longitude, and time. Then we constructed another program that interpolates the RUC model ABL data to the latitude, longitude, and time of the radio occultation measurements.
In this study we use two months of data, one summer month (July 2008) and one winter month (January 2009) to reveal seasonal variation of the ABL height. Then we created three graphs for each month: COSMIC ABL heights, RUC model ABL heights, and the differences of ABL heights. Then we compared the data.

Results

Figure 4 below shows the result for July 2008. The top image shows the COSMIC result, the middle image shows the RUC model result, and the bottom image shows the difference between COSMIC and RUC. You can see there is a significant difference in the ABL heights. You can also see that we have a lot of points across North America, and we hardly have any points in the Atlantic Ocean and the Gulf Coast.
Figure 4. See discussion above for the three plots above.

Figure 5 below shows the result for January 2009. The top image shows the COSMIC results, the middle image is the RUC model result, and the bottom image shows the difference between COSMIC and RUC. You can see that there is a significant difference in ABL heights, but there are some points that are relatively close in height to one another. There are also not that many points over land and along the east coast toward Canada, but there are a lot of points spreading out through the Gulf Coast region to the Atlantic Ocean.
Figure 5. See the discussion above for the three plots above.

If you compare the summer and winter seasons, you can see that the points that satisfied our matching criteria vary in location. You can also see that in the summer month there are more points over land than in the winter month, but there are also more points over the Atlantic Ocean and Gulf Coast in the winter than in the summer month. The ABL heights from the RUC model are always lower than the COSMIC measurements. In the winter month the RUC model ABL heights were higher than that of the summer month. COSMIC ABL heights seemed to stay
consistent between both seasons. The average ABL height for the summer month was 1778.53 meters with a standard deviation of 636.28 for COSMIC and 426.12 meters with a standard deviation of 426.12 for RUC: a vast difference. The average ABL height for the winter month was 1621.13 meters with a standard deviation of 629.58 for COSMIC and 770.98 meters with a standard deviation of 414.13 for RUC: still a vast difference. The RUC’s average is higher in the winter than in the summer, but this is the opposite for COSMIC: they are higher in the summer than in the winter.

The data led us to take a closer look at the Pacific Coast and only the points that overlie the Pacific Ocean because we have numerous data points over this region for both months.

Figure 6 shows scatter plots of the ABL heights along the Pacific Coast in summer: the top image is a plot of COSMIC ABL heights versus time, the middle image is a plot of RUC ABL heights versus time, and the bottom image plots RUC ABL heights versus COSMIC ABL heights. The time is in GPS seconds. You can see in the top plot that COSMIC has strong variability of different ABL heights at different times. The middle plot shows that RUC heights show less variability; there are only a few outliers. The last plot shows that there is little correlation between the RUC’s heights and COSMIC heights. You can see most of the points, but a few never go past the 1000-meter mark on the y-axis. So a lot of the ABL heights between the two methods do not agree.
Figure 6. See the discussion above for the three plots above.

Figure 7 shows scatter plots of the ABL heights along the Pacific Coast in winter: the top image is a plot of COSMIC ABL heights versus time, the middle image is a plot of RUC ABL heights versus time, and the bottom image plots RUC ABL heights versus COSMIC ABL heights. Again you can see that COSMIC has strong variability of heights in the top plot. RUC however shows a small variability of ABL heights; in the middle plot they are all clustered together. There still is low correlation between the ABL heights as shown in the bottom plot.
When comparing the summer and winter months, the RUC model’s heights are consistent for both months, while COSMIC showed variations of heights in each month. The RUC heights in the summer almost show a smooth line that it does not cross, but in the winter you have some peaks around 915000000 GPS seconds that you can see on the plot.

**Discussion**

From these results, we determined that the seasonal difference in the average ABL heights was due to thermal expansion, which is expected. That means the ABL expands in the summer and contracts in the winter—for COSMIC, but not for RUC. Therefore there were no comparison points over the Atlantic Ocean in the summer due to the water and air being warmer, so the RO didn’t detect a sharp layer. There were many comparison points in the Pacific Ocean because the water is naturally colder there. In the winter we acquired a lot of comparison points along the Gulf and Atlantic due to the temperature difference between the air and water. COSMIC generally does not produce many sharp ABL tops over land, but many were detected in the summer due to the criteria we chose for them, and the summer climate was suitable for obtaining a significant number over land.

When comparing ABL heights only along the Pacific Coast, RUC’s measurements were similar to each other, but a few comparison points were close to the COSMIC measurements. Over the oceans the level of atmospheric mixing is generally lower than over land. The mixing layer is typically around 500 meters over the ocean, which is the elevation that the RUC model generally reported its ABL heights off the Pacific Coast. RUC generated a few comparison points on the Pacific Coast that were closer to COSMIC measurements because the RUC model was not simulating clouds at those times. If clouds are in the area, the mixing layer is usually right below the clouds.

Both methods measure the ABL, but they measure different parts of the ABL. COSMIC is measuring where the strongest decrease in water vapor and humidity occurs. RUC on the other hand just reports the height that fits its definition (see image below); this might not always be the true ABL height.
Figure 8. This chart shows why the RUC and COSMIC methods may be producing different results for the ABL heights. —Chart from An Introduction to Atmospheric Boundary Layer Meteorology by Ronald B. Stull. You can see that the temperature stays constant with increasing altitude, then there is a decrease but it smooths back out to a constant temperature, then it decreases again. Since the RUC model only reports the first height that fits its definition, it marks the first decrease it finds as the ABL height—but COSMIC may take the second decrease due to the strong inversion layer.

Conclusion

We performed this research to determine which method is giving more accurate readings of ABL height. We have seen strengths in both methods, but we found that they’re both measuring different parts of the ABL. So we determined that the definition of the ABL was too vague. COSMIC is measuring where the strongest decrease in water vapor and humidity occurs. RUC on the other hand is just looking for the height that fits its definition. To better characterize how we measure the ABL height, we need to include turbulent mixing, temperature inversion, and a relative decrease in water vapor and humidity to improve accuracy. We were not able to produce high-precision comparisons between RUC and COSMIC ABL heights because our RUC model analysis did not include data for humidity, water vapor, and turbulence. From this research I hope we are able to start using COSMIC RO observations to determine the ABL for atmospheric models. This can improve the models’ skill in weather prediction. Over time I believe we will refine the definition of the ABL to enhance what exactly instruments measure.

Future Work

For future work I would like to look at more aspects of COSMIC and RUC. I would like to compare them over land and water and see how each method behaves at night and during the day. I would also like to locate a schematic of the ABL that shows the sub-cloud layer, the mixed layer, and the cloud layer. This can show how the temperature and dew point (or temperature and
mixing ratio) vary with height. Perhaps we can also find a way to measure the top of the cloud layer in RUC, and this could be compared to the COSMIC numbers rather than the RUC ABL top.

References


Stull, R.B., YEAR: *An Introduction to Atmospheric Boundary Layer Meteorology*. PUBLISHER, PAGECOUNT.