Using Radio Occultation Soundings to Study Mesoscale Convective Systems

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ABSTRACT

Mesoscale Convective Systems or MCS, formed particularly in the mid latitudes, are responsible for a great deal of damage especially in the summer time. These systems are hard to predict and forecast since many of the instruments used to collect data inside of them are not always reliable and are limited in use. A new satellite-based atmospheric limb sounding technique, called GPS radio occultation, has all-weather capability and may be able to provide vertical profiles of atmospheric parameters inside MCSs to help better understand these destructive storms. This study examines 9 GPS radio occultation observations from the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) that occur inside MCSs. We found that the COSMIC profiles consistently penetrate close to the surface and agree well with near-by radiosonde data in terms of refractivity, the fundamental atmospheric parameter provided by RO. However, the temperature and moisture retrievals that are estimated by a 1D variational assimilation procedure (i.e. a combination of RO refractivity and a first guess model) exhibit a dry bias that is currently under investigation.

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1. Introduction

A Mesoscale Convective System (MCS) is a complex of thunderstorms that typically occur at mid-latitudes during the warm season. Many MCSs are formed from different storms that originated at different locations and united in a specific area to form the system. These systems cause a significant amount of damage during their short lifetime. They are responsible for a large portion of the rainfall during the season and produce many flash floods in the United States. Some MCSs produce other severe weather phenomena such as strong winds, hail, tornadoes, and strong electrical storms. Almost one out of every four MCSs results in injuries and death (Maddox et al. (1986)), which is why it is important to fully understand these systems.

These types of phenomena are difficult to forecast. Unfortunately, many upper-air observational systems, such as radiosondes, do not always provide reliable information above or inside precipitating systems, which would help us better understand and predict their development. Radiosondes also provide only a limited amount of information to study MCSs because they are launched only twice a day from relatively few ground sites.

The purpose of this research is to evaluate a new technique that may provide us with useful and better information to increase our knowledge on these big systems. We examine several cases of MCS using an innovative technique called Global Positioning System or GPS radio occultation (RO). This new technique uses GPS signals to retrieve atmospheric properties important for weather forecasting and other kinds of research. Radio occultation was first used in planetary missions to comprehend the dynamics of other planets' atmospheres in the solar system. But since 1995, radio occultation has been used to understand the Earth's atmosphere with great success in several missions. The newest and improved mission is called COSMIC (Constellation Observing System for Meteorology Ionosphere & Climate), a six-satellite constellation that was launched in April 2006. In our research we examine COSMIC sounding data that coincided with MCSs. The locations of the MCSs were identified by means of infrared satellite images for the time periods of May-July 2006 and April-July 2007 in the United States. GPS RO is a promising new technique for studying MCSs since it provides high vertical resolution atmospheric profiles, is independent of cloud and precipitation, and provides many globally distributed soundings per day (.e.g. cosmic is designed to provide 2500 soundings per day). To validate our data inside of unstable systems such as MCSs, COSMIC data were compared to near-by radiosondes, model forecasts and model analyses.

This is the first time COSMIC radio occultation will be used to study MCSs. This research could provide new information about the vertical structure of MCSs, which would be valuable in improving our understanding of their development and possibly lead to improved forecasting of these disastrous events in the future.

2. Methods

This research was carried out at the University Corporation for Atmospheric Research (UCAR) COSMIC Project Office. The COSMIC Data Analysis and Archive Center (CDAAC) processes all COSMIC data into vertical profiles in near real-time that are then forwarded to national weather centers for operational data assimilation. CDAAC contains a variety of data from four different missions: the first one is GPS/Meteorology (GPS/MET) which includes data from April 22, 1995 to February 16, 1997; the second one was the Satélite de Aplicaciones Científicas-C (SAC-C) which was active during the periods of August 13, 2001 until November 15, 2002; the third is the CHAllenging Mini Payload Satellite or CHAMP, May 19, 2001-Present; and the last one COSMIC's six microsatellites which has been running since April 14, 2006. All these missions produced atmospheric sounding data during the past 12 years. The research presented here analyzes data from the COSMIC because of its large number of soundings and high vertical resolution (i.e. ~ 1.5 km above the troposphere and ~ 0.1 – 0.5 km in lower troposphere). Also, a new COSMIC open-loop tracking technique allows the RO soundings to penetrate closer to the surface than with previous missions. The COSMIC micro-satellites contain a GPS radio occultation receiver. The two GPS signals (L1 at 1575.42 MHz and L2 at 1227.6 MHz) are delayed and bent when passing through Earth's atmosphere because of its vertical refractivity gradient, see Figure 1.

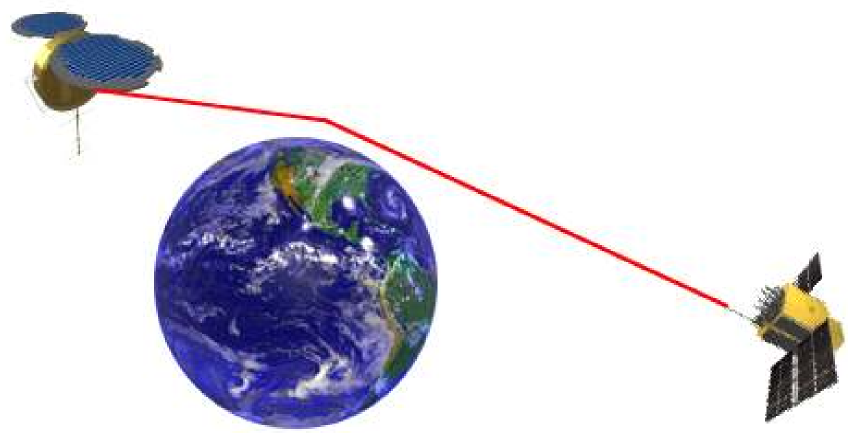

Figure 1: As the GPS signal travels through Earth's atmosphere the signal is delayed and bent because of the vertical gradient of refractivity.

A processing flow diagram for the radio occultation technique is shown in Figure 2. The phase and amplitude of the GPS signals are measured at the Low Earth Orbiter or LEO. Then, with precise knowledge of the position and velocity of the GPS and COSMIC satellites, the ray bending profile is computed for each L1 and L2 signal. A linear combination of the L1 and L2 bending angles is used to remove the effect of the ionosphere refraction and produce an ionosphere-free bending angle profile. This ionosphere-free bending angle is then inverted to obtain atmospheric refractivity as a function of height. Although the inverted refractivity profile has high vertical resolution, the horizontal resolution is lower, ~200 km, due to the limb sounding geometry.

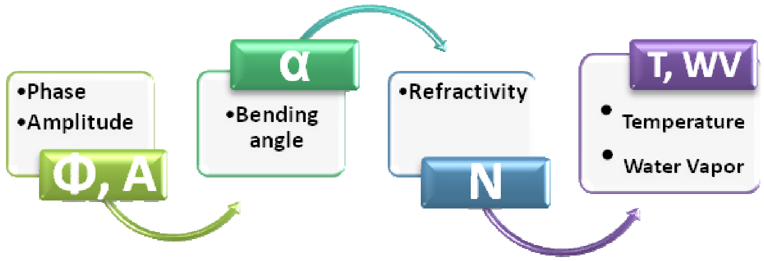

Figure 2: Processing flow diagram of the radio occultation technique.

As seen in the following equation, refractivity is a function of pressure (P in mbar), temperature (T in degrees K), and water vapor pressure (P_w in mbar), properties important for weather forecasting and other kinds of research:

$$N = 77.60\left(\frac{P}{T}\right) + 3.730 \times 10^5 \left(\frac{P_w}{T^2}\right)$$

The fundamental RO observable is atmospheric refractivity. In order to separate the effects of temperature and moisture from the RO refractivity, and retrieve profiles of kinetic temperature and water vapor pressure, additional information is required. The CDAAC uses a method called One-dimensional Variational (1D-Var) to combine the information of the GPS radio occultation with a priori (1^{st} guess) information from an atmospheric weather model. In near real-time operations, CDAAC uses the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) forecast as 1^{st} guess information in the 1D-Var retrieval. In this research we also use the European Centre for Medium-Range Weather Forecasts (ECMWF) high resolution model as a 1^{st} guess to determine the sensitivity of the 1D-Var retrieval to 1^{st} guess information. More details regarding the characteristics and processing strategies of GPS RO can be found in Rocken et al. (1997), Kuo et al. (2004) and Ware et al., (1996).

To match the COSMIC soundings with MCSs, we first look at an infrared image archive in http://locust.mmm.ucar.edu/ to locate the time and place of MCS systems. An infrared image is a measure of cloud top temperature. The higher the cloud the cooler it is, making it easy to locate the MCSs on the infrared image. After locating the systems we go to CDAAC and compare the infrared images with the radio occultation map of that day. When there is a match of a COSMIC sounding with an MCS, the 1D-Var temperature and water vapor profiles are compared with near-by radiosondes and other models such as the ECMWF high resolution model and the NCEP GFS (previously AVN) forecast.

3. Results & Discussions

For this research, nine cases were identified with radio occultation soundings that coincided with MCSs in time and location. Three case studies are presented. In Figure 3a, the

MCS is spotted with the radio occultation located on May 7, 2007. In Figure 3b, the closest radiosonde in time and location to the radio occultation was also identified.

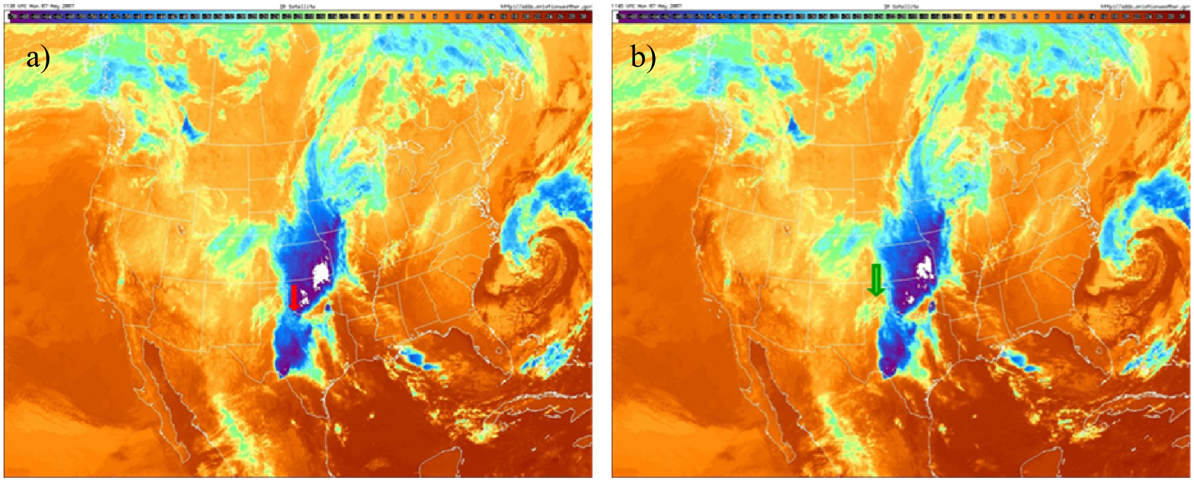

Figure 3: a) MCS on May 7, 2007 with radio occultation location at 34.15˚N, 99.41˚W at 11:22 UTC (red arrow) b) Radiosonde location at 35.23˚N, 101.70˚W at 12:00 UTC (green arrow)

Then the radio occultation 1D-Var temperature and water vapor data was plotted in the same graph with radiosonde, ECMWF high resolution model, and NCEP GFS (AVN) forecast, as shown in Figure 4 (a) and (b).

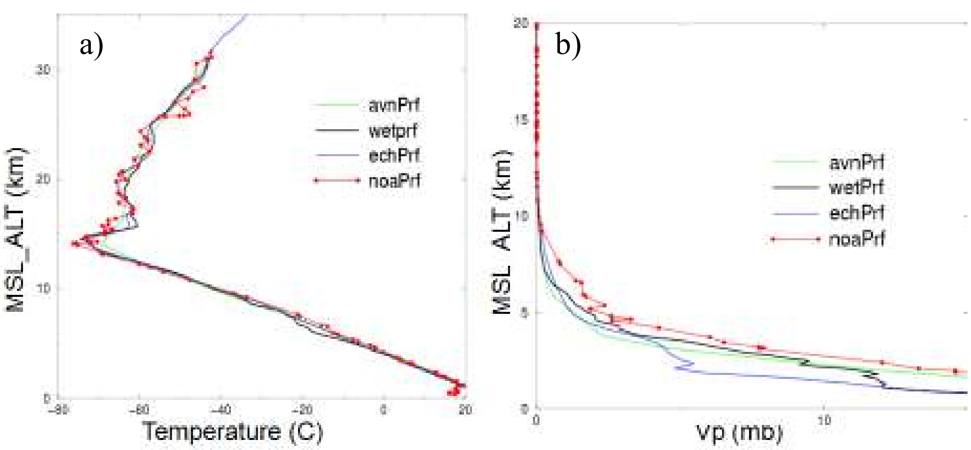

Figure 4: May 7, 2007 a) Temperature vs. altitude where avnPrf is the NCEP forecast, wetPrf the radio occultation sounding, echPRF the ECMWF high resolution model, and noaPrf the radiosonde b) water vapor vs. altitude

There are some interesting features that can be pointed out from the figures above. It is important to notice that from the temperature plot, figure 4a, the radio occultation can detect small-scale structures that models cannot pick up. Some examples are the waves above the tropopause which the radiosonde also detects. One definition of the tropopause is the region or point where the temperature stops decreasing and starts increasing rapidly. The radio occultation sounding senses the tropopause very well, which is validated by the radiosonde. Although the models can detect this temperature inversion too, they suffer from poorer vertical resolution. In addition, some temperature fluctuations are present in the lower troposphere. The causes are unknown but maybe they can provide us with some information about the system in further studies. The radio occultation sounding is also capable of penetrating near the surface which can give a nearly complete profile of the vertical characteristics for that specific location.

Now if we look at figure 4b some discrepancies are present that are worth mentioning. The radiosonde and radio occultation water vapor soundings are not as similar as in the temperature plot. The radiosonde seems to have more moisture than the radio occultation which is not what we would expect given that the radio occultation is inside the system and the radiosonde is outside. However, it is important to remember that radiosondes are from a slightly different time and location than the radio occultation which might contribute to the discrepancy that we are seeing. Furthermore, the radio occultation is more comparable to the models than the radiosonde.

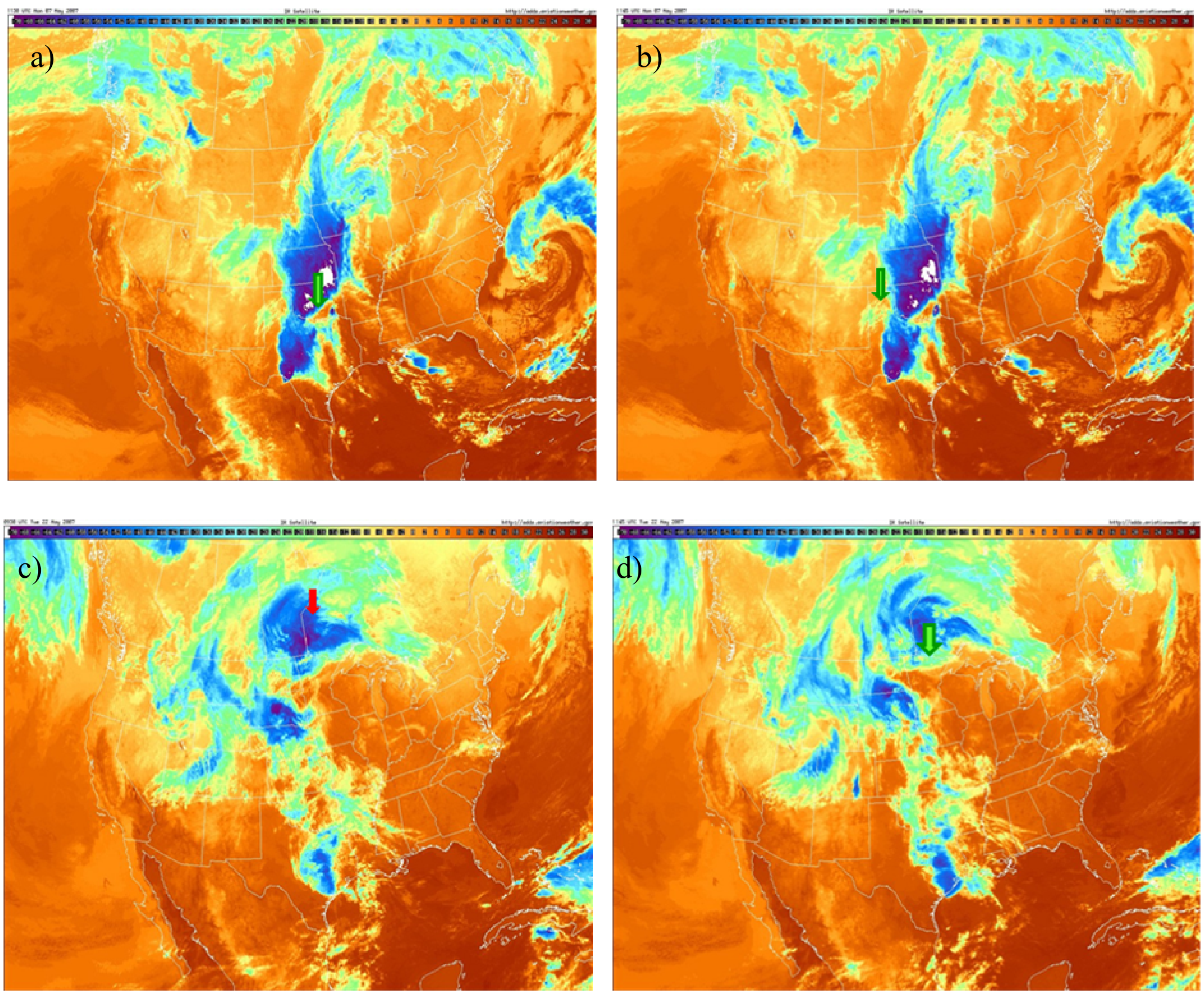

Figure 5: a) MCS on May 7, 2007 with radio occultation location at 35.28˚N, 97.59˚W at 11:03 UTC b) Radiosonde on May 7, 2007 with location at 35.23˚N, 101.70˚W at 12:00 UTC c) MCS on May 22, 2007 with radio occultation location at 52.81˚N, 93.58˚W at 09:29 UTC d) Radiosonde on May 22, 2007 with location at 48.57˚N, 93.38˚W at 12:00 UTC

Let us look at two more cases and see if our observations are consistent. Figure 5 a-d, shows the two other cases: May 7, 2007 at 11:03 UTC and May 22, 2007 at 09:29 UTC. The maps illustrate clearly the locations of the radio occultations and radiosondes, inside and outside of the MCS, respectively.

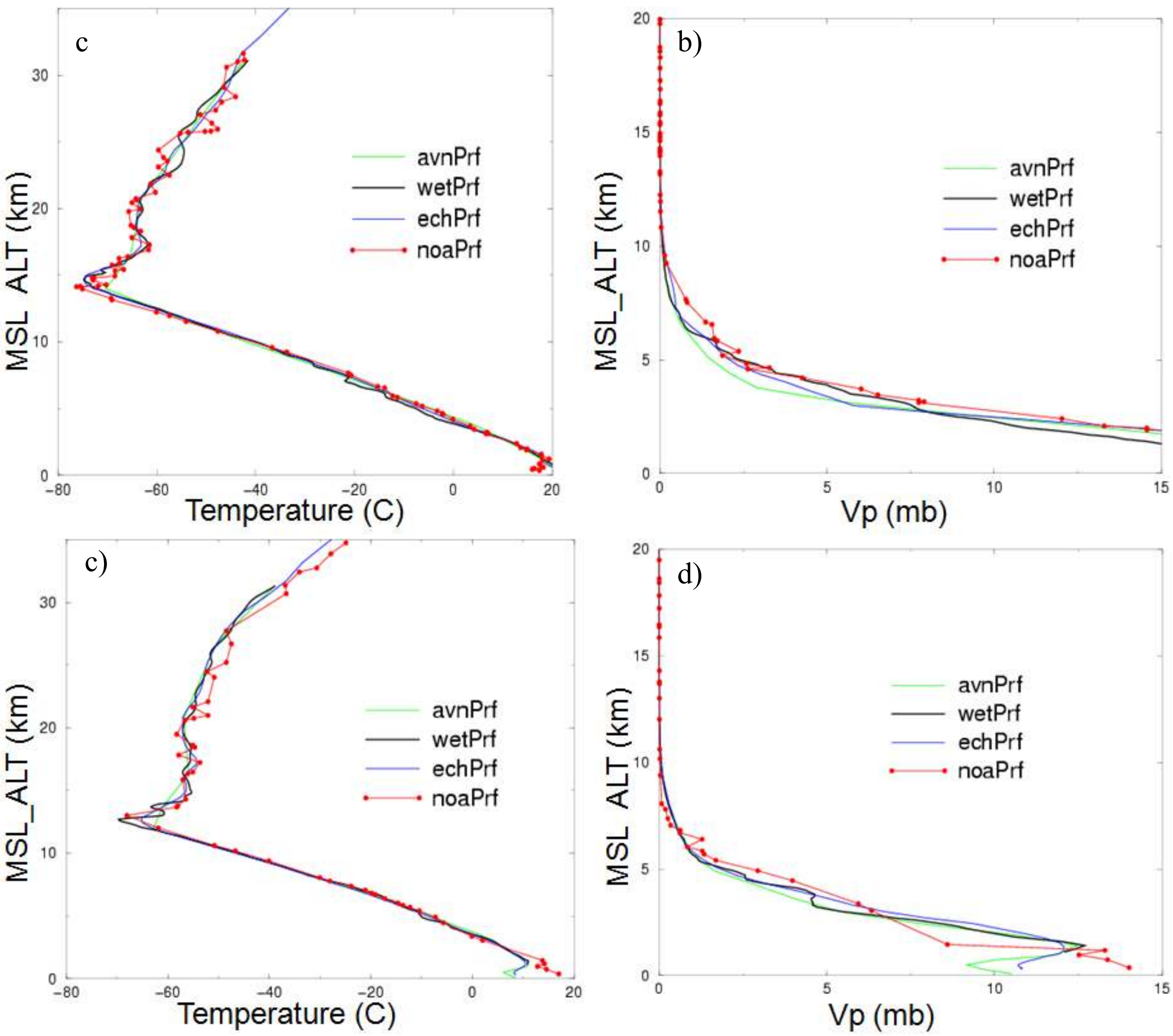

Figure 6: May 7, 2007 at 11:03 UTC a) Temperature vs. altitude where avnPrf is the NCEP forecast, wetPrf the radio occultation sounding, echPRF the ECMWF high resolution model, and noaPrf the radiosonde b) water vapor vs. altitude, May 22, 2007 at 09:29 UTC c) temperature vs. altitude d) water vapor vs. altitude

From Figure 6 a-d similar features can be observed as in the first case: waves above the tropopause, produce rather well the tropopause, temperature fluctuations, good penetration near the surface, and major discrepancies in the water vapor plot. To help us better understand the observed inconsistencies, and see how realistic the radio occultation sounding is inside of an MCS, a skew-T/log-P chart was used. We also changed the 1st guess in the 1D-Var retrieval from NCEP forecast to ECMWF high resolution model to observe if there were differences in the temperature and water vapor retrievals. In a skew-T/log-P diagram, the y-axis is labeled as pressure displayed in a log scale measuring in hPa. The temperature is skewed at 45 ˚ in the graph. The other three axes are moist adiabatic, mixing ratio, and dry adiabatic as shown in Figure 7.

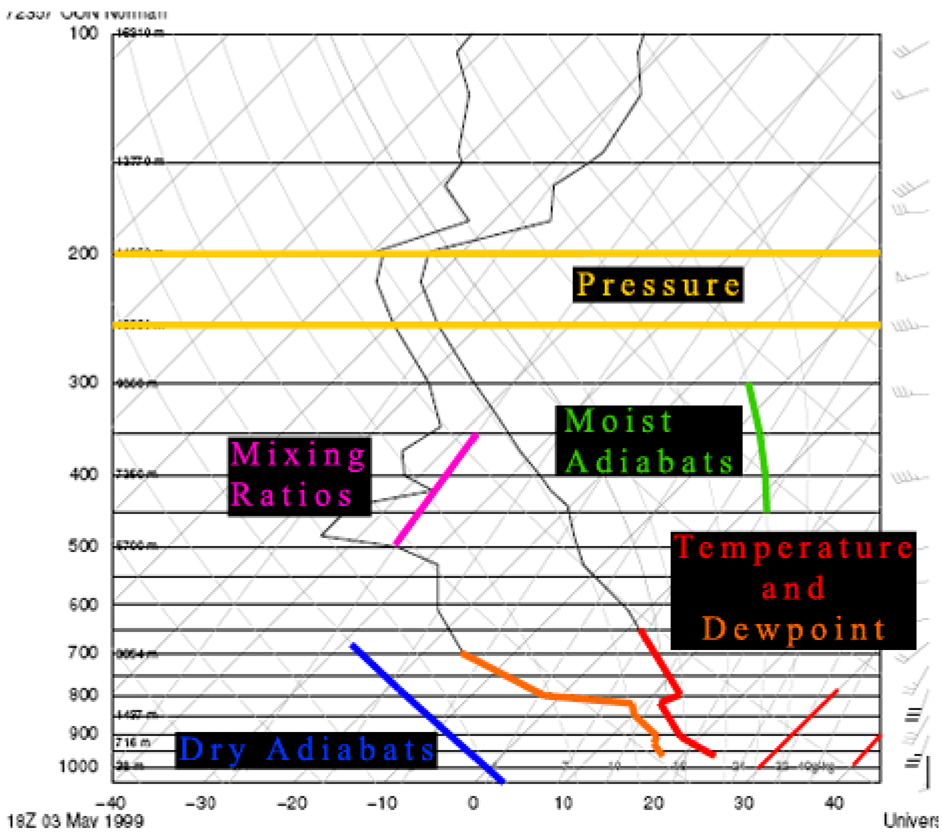

Figure 7: Example of a skew-T/log-P diagram with the axis labeled. From the website http://www.personal.psu.edu/smd293/meteo482/overview.html

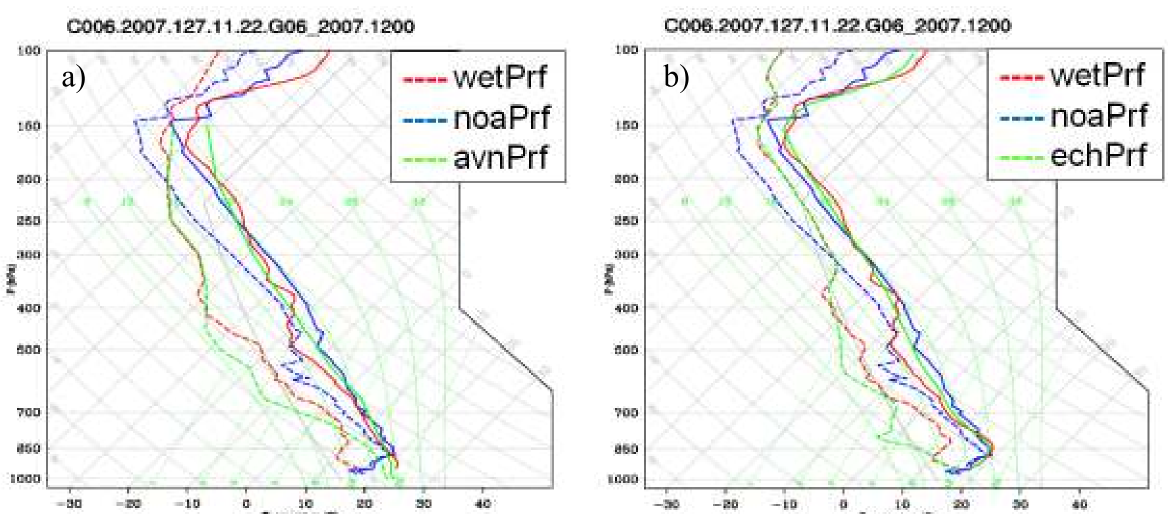

Figure 8: May 7, 2007 at 11:22 UTC The solid and dashed line are the temperature and dew point temperature respectively a) Skew-T/log-P chart with wetPRF, noaPrf, and avnPrf using for the wetPrf retrieval the NCEP forecast as a 1st guess. b) Using the ECMWF high resolution model as a 1st guess for the wetPrf retrieval.

Shown in Figure 8a is the skew-T/log-P diagram for the first case. The red lines correspond to the radio occultation data with the solid and dashed line its temperature and dew point temperature, respectively. The blue lines represents the radiosonde data and the green lines the NCEP forecast (in Figure 8b, the green line represents the ECMWF high resolution model). In a skew-T/log-P diagram it is easier to identify when there is saturation and at what altitude (or pressure level) this is happening in the atmosphere. This occurs when the dew point temperature (dash line) and the temperature (solid line) are very close together indicating a nearly 100 % humidity making it possible for condensation. This is an indication of the existence of clouds, and for a big system such as an MCS saturation is expected and should be observed relatively easily. If we look at Figure 8a for example, we see this characteristic in the radiosonde but not in the radio occultation sounding as expected. Another trait that is important to notice is the difference in the curves of the radio occultation between Figures 8a and 8b when the 1st guess is changed. This tells us that the 1DVAR method is sensitive to the 1st guess model that is used for the temperature and water vapor retrieval. We can see the same features in the skew-T/log-P of the other two cases as it shown in Figure 9.

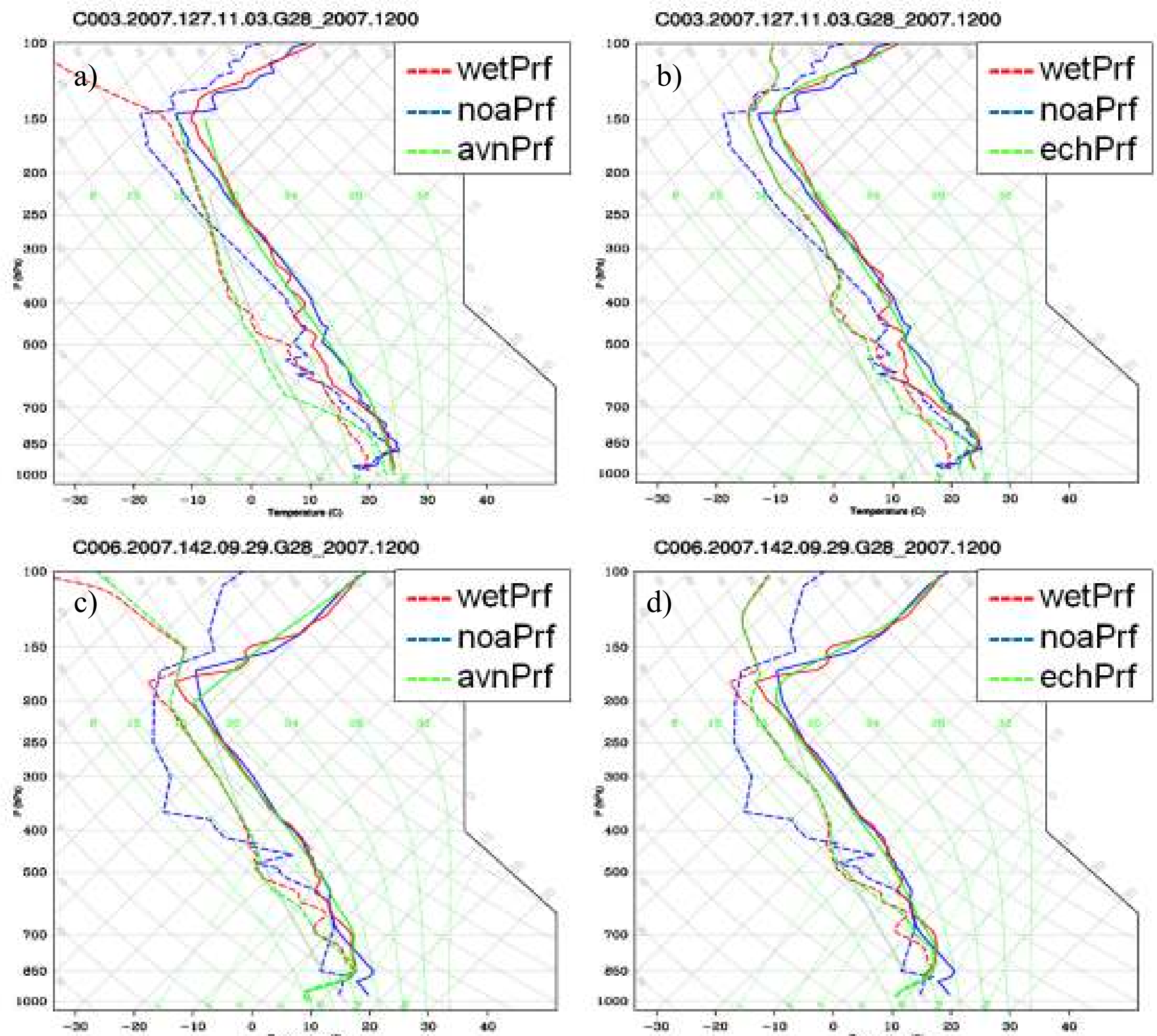

Figure 9: May 7, 2007 at 11:03 UTC a) Skew-T/log-P chart using for the wetPrf retrieval the NCEP forecast as a 1st guess. b) Using the ECMWF high resolution model as a 1st guess for the wetPrf retrieval. May 22, 2007 at 09:29 UTC c) Skew-T/log-P chart using for the wetPrf retrieval the NCEP forecast as a 1st guess. d) Using the ECMWF high resolution model as a 1st guess for the wetPrf retrieval.

To help understand some of the discrepancies observed in the previous results, the refractivity profiles of the radio occultation, the radiosonde, and the NCEP forecast were statistically compared as is shown in Figure 10.

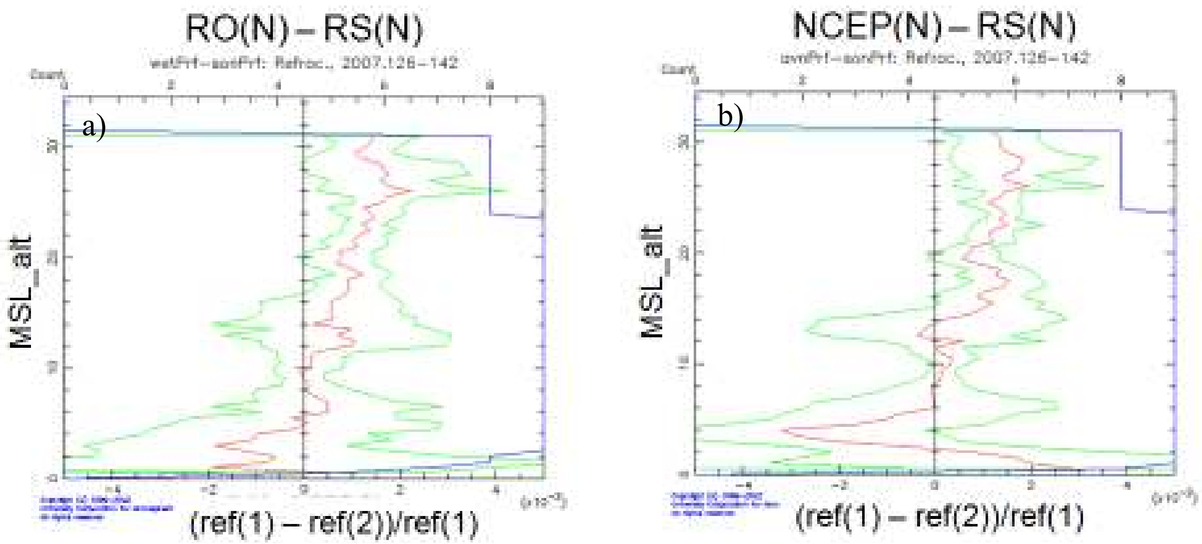

Figure 10: Statistical calculation for the refractivity profile. The top axis is the number of cases which is indicated by the blue line. The green line represents one standard deviation and the red line the mean error. a) Refractivity comparison between radio occultation, b) between NCEP forecast and radiosonde

From this Figure it is clear that above the 10 km the difference between the two plots are negligible, although it is important to notice that both of them tend to go to the right. Since the radiosonde is present in both plots, this may suggest that it may have a systematic bias, although we can interpret it also that the radiosonde is correct and the radio occultation and NCEP forecast are wrong. But the most interesting part of the plots is the difference below the troposphere between them. In Figure 8b there are larger mean errors below 6 km than in Figure 8a, which implies that the radio occultation refractivity profiles agree with radiosonde data as well or better than the NCEP forecast model. However, strong conclusions cannot be made from these plots due to the small number of observations.

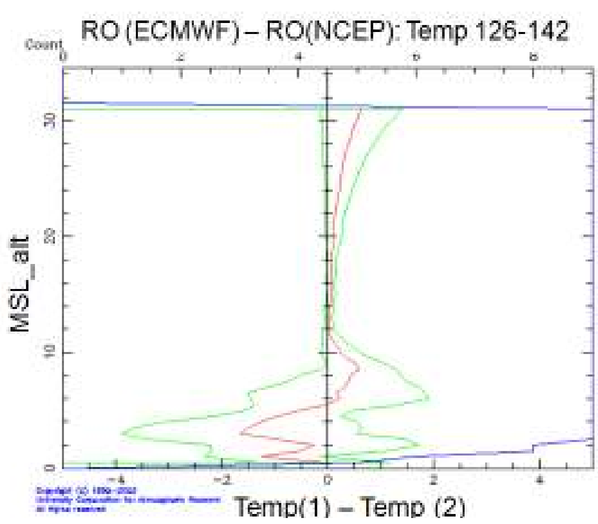

Figure 11: Temperature comparison between radio occultation 1D-Var retrievals using 1st guess as NCEP forecast and ECMWF high resolution model

When the 1D-Var retrievals were compared when changing the 1st guess, an interesting factor was encountered. Above 10 km the difference is small, but as we go near the surface, especially below the 5 km, where there is more moisture present, the differences increase. Therefore, the 1DVAR method for deducing the temperature and moisture from refractivity is sensitive to the 1st guess model in the lower troposphere. But the question still remains whether it is more sensitive inside an MCS, because of the higher moisture present, than outside of the system or if the sensitivity the same. To help understand this situation, eleven cases were chosen with radio occultations far from the MCS systems on the same days.

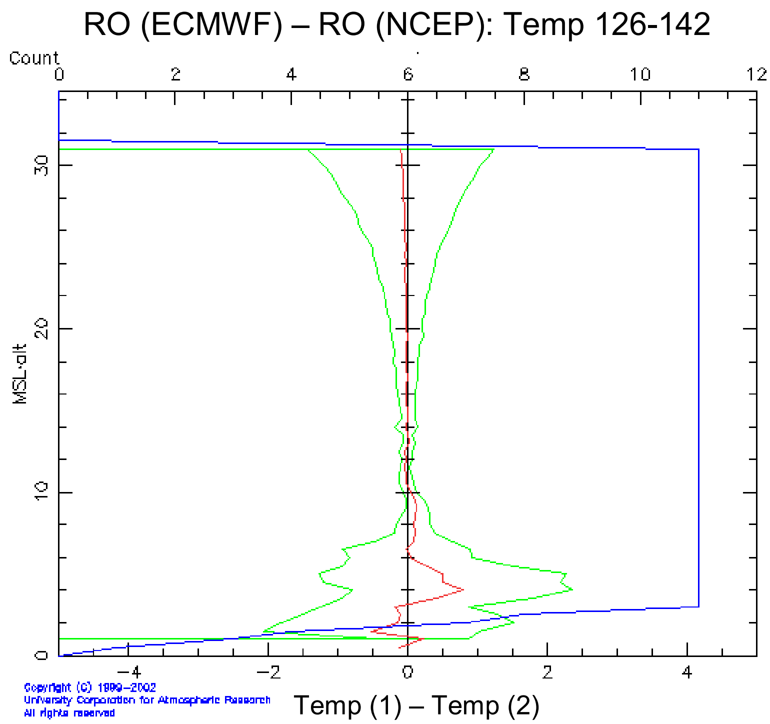

Figure 12: Temperature comparison between radio occultation wetPrf using 1st guess NCEP forecast and ECMWF high resolution model

Figure 12 shows the same plot as Figure 11 for the eleven cases outside of MCSs. It is clear that the mean difference decreased greatly in this situation; however the difference is still significant in the first 5 km. It is also important to point out that we studied a small number of cases and it is necessary to include a larger number of cases to make the results more statistically significant.

4. Conclusion

This research tried to determine whether COSMIC RO could give realistic soundings inside of an MCS and provide us with a new technique to study such systems. From the radio occultation data is clearly reliable given that it can detect small scale vertical structures which could give us valuable information of the dynamics of MCSs. Furthermore, COSMIC is able to penetrate near the surface which previous missions were unable to do, and that provides more valuable data in that region. We found that the radio occultation's refractivity is consistent with radiosonde's refractivity. This tells us that the inversion of the bending angle to obtain this property is consistent with other data sources. However, the larger uncertainties in the retrieved

1D-Var COSMIC soundings in the bottom 5 km indicate that the 1DVAR method is sensitive to the 1st guess.

Future work will focus on gathering more cases to have a more complete study in a statistical sense. Attempts will be made to improve the 1DVAR method by including additional or better 1st guess. Another possibility is to assimilate refractivity into a high resolution mesoscale 3DVAR system. RO retrievals can give us new information on MCSs that may help us understand and forecast them better and hopefully minimize damage from these disastrous events.

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